THE EFFECT OF WEAVING MANEUVERS ON OPERATION OF A FREE RIGHT-TURN LANE AT RAMP TERMINALS

A Thesis

by

MINCHUL PARK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Yunlong Zhang
Committee Members,	Mark Burris
	Thomas Wehrly
Head of Department,	David Rosowsky

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ABSTRACT

The Effect of Weaving Maneuvers on Operation

of a Free Right-Turn Lane at Ramp Terminals.

(December 2005)

Minchul Park, B.S., Kyung Hee University

Chair of Advisory Committee: Dr. Yunlong Zhang

Service interchange ramp terminals provide access from the local highway or urban street system to the freeway. In urban areas, the ramp terminals at the arterial road are usually signalized for separation of all high-volume conflicting movements. If right-turn or other movements exiting from the ramp terminals are high, a free right-turn lane, which improves operations for right-turn and through exiting traffic, is sometimes provided at the ramp terminals with an exclusive lane for right-turn vehicles on a departure leg.

If the ramp terminal is closely followed by the next downstream intersection, weaving maneuvers will occur since some vehicles make a right turn at the ramp terminal and make a left turn at the downstream intersection. These weaving vehicles usually slow down or stop on the free right-turn lane in order to find an acceptable gap in the arterial road traffic. These slowing or stopping vehicles may cause safety and operational problems. This research evaluates the effect of these weaving maneuvers on the operations of a free right-turn lane at the ramp terminals.

To provide a means for evaluating free right-turn lane operations, a linear regression model was developed to predict the delay on the free right-turn lane caused by stopped or slowed vehicles planning on making a weaving maneuver. The variables for this model were arterial through volumes, weaving volumes, number of lanes, and ramp spacing within the interchange. The regression model was based upon the results of the CORSIM traffic simulation model that was calibrated using field data obtained from the study site in College Station, Texas.

Once the predicted model was developed, the model validation was performed using the field data to check the accuracy of its prediction. A statistical measure was performed for quantifying the difference between the observed and predicted delay on the free right turn lane. From the research results, it was concluded that the weaving maneuvers influence the operation of a free right-turn lane and cause delay on the free right-turn lane.

ACKNOWLEDGMENTS

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I would also like to thank my family, mother, elder brother and sister-in-law, for the opportunity given me to undertake this journey into the cutting edge of transportation research at Texas A&M University and their support throughout my graduate studies. Finally, the author would like to thank God for the awesome strength and abundant grace given to him to complete this thesis.

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CHAPTER I

INTRODUCTION

Over the past several years, funding for new roadways didn't meet the demand of traffic volumes in urban and suburban areas (*1*). Moreover, opportunities to increase roadway capacity by building additional roadway are reducing. The remaining alternatives for increasing the roadways' capacities are to improve traffic flow through operational techniques such as accurate and standardized analysis tools.

The *Highway Capacity Manual* (*HCM*) (*2*) and related computer software packages provide such tools to analyze roadway operations. Despite the available tools to the traffic engineer, however, research for certain types of roadway, such as weaving areas, is not adequate to analyze their operation. As defined in the HCM, "weaving areas are formed when a merge area is closely followed by a diverge area, or when an on-ramp is closely followed by an off-ramp and the two are joined by an auxiliary lane (*2*)." In the case of arterial weaving areas, vehicles exiting from the freeway merge with the arterial traffic flow at the ramp terminal and then diverge from the arterial traffic flow at the downstream intersection. Messer (*3*) mentioned that these arterial weaving maneuvers may cause turbulence in the traffic stream, and this section generally experiences operational problems and reduced capacity because of weaving maneuvers within this section (*3,4*).

This thesis follows the style and format of the *Transportation Research Record*.

In this thesis, weaving vehicle are the vehicles making a right turn at the ramp terminal followed by a left turn at the downstream intersection, and this weaving section has been classified as a Type C weave section, as described in Chapter 13 of the HCM (*2*).

Weaving maneuvers may occur on freeway, multilane highways, two-lane highways, interchange area, urban streets, or collector-distributor roadways (*2*). The HCM methodology was developed for freeway weaving analysis but could be used as guidance for adapting the procedure to weaving segments on multilane highways. It is also defined in the HCM that "the procedures are not appropriate for analysis of weaving on urban areas involving signalization issues, but could be used with an approximation for weaving areas on urban streets (*2*)." However, McShane and Roess (*5*) pointed out that the HCM procedure should not be used to analyze weaving sections that contain traffic signals.

PROBLEM STATEMENT

Arterial weaving section, particularly between an interchange ramp terminal and the next closely-spaced signalized intersection, can amplify the amount and severity of lane changes that occur and can lead to operational and safety problems. However, most models of weaving maneuvers have been developed for freeway sections (*2*). High turning volumes and the close spacing between ramp terminal and the downstream intersection in urbanized areas can create severe operational problems on the cross street, including the effects of weaving and arterial congestion. Adequate separation between the ramp terminals of the interchange and the next downstream intersection should be provided to promote safe and efficient traffic operations.

As defined in *A Policy on Geometric Design of Highways and Streets* (*Green Book*) (*6*), "access separation and access-control distances between a free right-turn ramp and an adjacent intersection should be considered when a free right-turn lane is installed for improved operations of exiting traffic." In The Green Book, these considerations include "the distances needed to enter and weave across the through-traffic lanes, move into the left-turn lane, store left turns with a low likelihood of failure, and extend from the stop line to the centerline of the intersecting road or driveway (*6*)."

Existing guidelines provided in the HCM and the Green Book are not enough to provide a complete description of free right-turn lane operations at the ramp terminals. Three geometric designs at ramp terminals of a diamond interchange may be considered for right-turn movements: exit ramp with a shared right-turn lane, an exclusive right-turn lane, or a free right-turn lane. Although right turns face a conflicting vehicular flow in the shared right-turn lane, the exclusive right-turn lane is used only by vehicles making those turns (*7*). Right-turning drivers need to stop to wait for safe turning opportunities on exclusive right-turn lanes because of conflicting through movements on the cross street. In the case of free right-turn lanes, however, right-turning drivers do not need to stop if there is an exclusive lane for right-turn vehicles on a departure leg because right-turn traffic is unaffected by upstream or downstream conditions, and it should be removed entirely from the analysis if there is no signal control for free right turns (*2*).

Although stopping vehicles usually are not expected on a free right-turn lane having an exclusive lane for right-turn vehicles on a departure leg, several stopping vehicles were observed on the free right-turn lane during green signal phases for the arterial road at this site. These unexpected stopping vehicles may cause safety and operational problems because the following vehicles' drivers generally expect that the front vehicle will not stop on the free right-turn lane. In this study, it was observed that most vehicles stopping on the free right-turn lane turned left at the downstream intersection. As discussed earlier, the section studied in this thesis is Type C weaving section.

Another problem which a practicing engineer may face is replicating the phenomena of arterial weaving movement with a traffic simulation. As explained by Lloyd (*8*), it appeared that TRAF-NETSIM (*9*) simulated the arterial weaving section very well with its microscopic simulation. The latest release of the TRAF-NETSIM model is the CORSIM (*10*) microscopic traffic simulation model, and this CORSIM simulation was used for the analysis in this thesis.

RESEARCH OBJECTIVES

The objectives of this research were divided into two parts. The first objective of this study was to analyze the data collected at an arterial section between a ramp terminal of a diamond interchange and the next downstream intersection in College Station, Texas. The second objective was to analyze the data collected from the computer simulation model and to develop an analytical model for describing the free right-turn lane operations.

The research effort for these objectives was focused on the effects of weaving maneuvers on the operation and delay of a free right-turn lane under various traffic and geometric conditions such as arterial through volumes, weaving volumes, the number of lanes, and signal progression and distance between two ramp terminals. The objectives are met by specifically achieving the following tasks:

- Perform a literature review of weaving maneuvers, signal phases for a diamond interchange, and traffic computer simulation models;
- Collect and analyze field data on an arterial weaving section between a ramp terminal and a downstream intersection;
- Perform simulation runs using CORSIM microscopic traffic simulation program;
- Collect and analyze data on an arterial weaving section through the use of CORSIM;
- Formulate an analytical model to predict the operations and delay of a free right-turn lane by using data collected from the simulation program;
- Evaluate the selected model's capabilities by using field data; and
- Draw conclusions based on the outcome of the study.

ORGANIZATION OF THESIS

This thesis contains a total of five chapters and two appendices. Chapter I describes the problems addressed by this study and establishes the research objectives. The literature review that was conducted as part of the research is provided in Chapter II. This discussion includes an introduction to freeway weaving models, previous works of arterial weaving section between a ramp terminal and downstream intersection, geometric conditions and signal phases of a diamond interchange, and computer simulation. Chapter III contains a description of the methodology followed in the study. This includes procedures of the data collection and reduction along with the steps undertaken to calibrate and use the computer simulation model. The results of the field data collection and analyses, the computer simulation, the model development process, and the model validation are presented in Chapter IV. Chapter V presents the conclusions of this research along with recommendations for further research.

CHAPTER II

LITERATURE REVIEW

This chapter contains the results of the literature review that was carried out to investigate the state of the art in freeway weaving models, arterial weaving models, and diamond interchanges. The computer simulation model that was available for this study was also discussed.

FREEWAY WEAVING

The 2000 HCM defines a weaving maneuver as "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway without the aid of traffic control devices (*2*)." A simple weaving maneuver that is formed by a single merge point followed by a single diverge point is illustrated in Figure 2.1. This weaving maneuver is found on every type of roadway. However, the focus of research and investigation has been for freeway weaving, and several models have been developed for analysis of freeway weaving sections.

The first method for analyzing freeway weaving sections was provided in the 1950 HCM (*11*). The objective of the first method was to predict the capacity and operating speeds in the freeway weaving section. The revised version of the method presented in the 1950 HCM was provided in the 1965 HCM, and this revised methodology for freeway weaving sections was focused on the quality of flow (*12*).

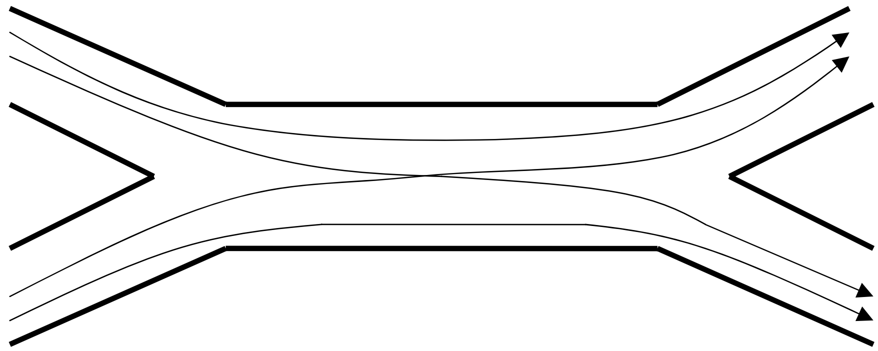


Figure 2.1 Simple Weaving Maneuver

The capacity and speed of the weaving and non-weaving vehicles are usually considered as the measures of effectiveness (MOEs) for the freeway weaving section. Transportation Research Board Circular 212, *Interim Materials on Highway Capacity* (*13*) documented the results of the study for freeway capacity analysis procedures in the late 1970s. This document also presented a second weaving area methodology developing weaving and non-weaving speeds for simple weaving section. The methodology to predict average operating speeds of weaving and non-weaving vehicles was provided in the 1985 HCM. The final weaving procedures for reducing the underestimating speeds of weaving and non-weaving vehicles are also documented in the HCM 2000 (*5*).

The HCM 2000 provides the following equations for predicting the average speeds of weaving vehicles and non-weaving vehicles (*2*):

$$S_i = 15 + \frac{S_{FF} - 10}{1 + W_i} \tag{1}$$

$$W_i = \frac{a(1+VR)^b (v/N)^c}{(3.28L)^d} \tag{2}$$

where: a,b,c,d = constants;

S_i = Average speed of weaving (i=w) and non-weaving (i=nw) vehicles in section (mph);

S_{FF} = Free-flow speed of freeway (mph);

W_i = Weaving intensity factor for prediction of weaving (i=w) and non-weaving (i=nw) speeds;

VR = Volume ratio (ratio of weaving to total traffic in section);

v = Total demand flow rate in section (vph);

N = Number of lanes in weaving section; and

L = Length of weaving area (ft).

Since lane changing behavior within a weaving section is the most critical aspect of operations in weaving maneuvers, a critical geometric characteristic that can affect weaving performance and classification of weaving types is configuration (*2*). The configuration is considered as the relative placement and the number of entry lanes and exit lanes for the weaving section, so this configuration can have major influence on how much lane-changing is needed for weaving vehicles to complete successfully their maneuver within the weaving section (*2*).

As shown in Figure 2.2, the most common Type A weaving section is formed by a one-lane on-ramp followed by a one-lane off-ramp (*2*). The major characteristic of Type A configuration is that all weaving vehicles must make one lane change to execute their maneuver successfully. The lane line between the auxiliary lane and the right-hand freeway lane is called the crown line, and in the case of Type A configuration all weaving vehicles must make a lane change across the crown line (*2*). Thus, weaving vehicles usually occupy the two lanes adjacent to the crown line within a Type A weaving section.

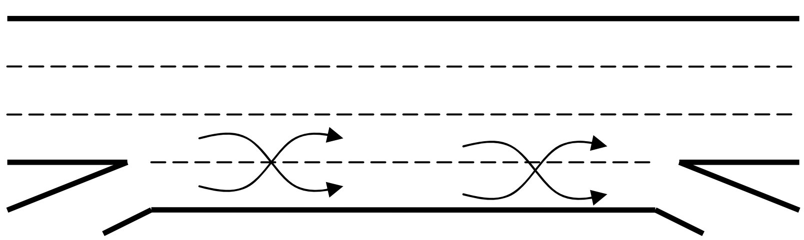


Figure 2.2 Type A Weaving Sections

Figure 2.3 illustrates a common Type B weaving section. In the case of Type B weaving section, one weaving movement can be completed without a lane change while the other movement must one lane change (*2*). As shown in Figure 2.3, since a through lane is provided for at least one of the weaving movements, Type B weaving configurations are efficient in carrying large weaving volumes (*2*).

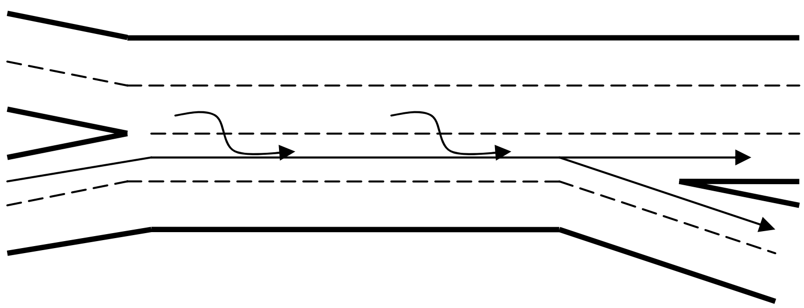


Figure 2.3 Type B Weaving Sections

As shown in Figure 2.4 (a), a Type C weaving section is similar to a Type B due to one or more through lanes provided for one of the weaving maneuvers (*2*). One weaving movements can be completed without a lane change in this type section. However, the other vehicles must change at least two lanes for their weaving maneuvers. In the second case of Type C (a two-sided weaving section) as illustrated in Figure 2.4 (b), a weaving movement is accomplished from a right-hand on-ramp to a next left-hand off-ramp, or vice versa (*2*). Thus, the vehicles must cross all lanes from one side of the freeway to the other for their desired maneuver (*2*).

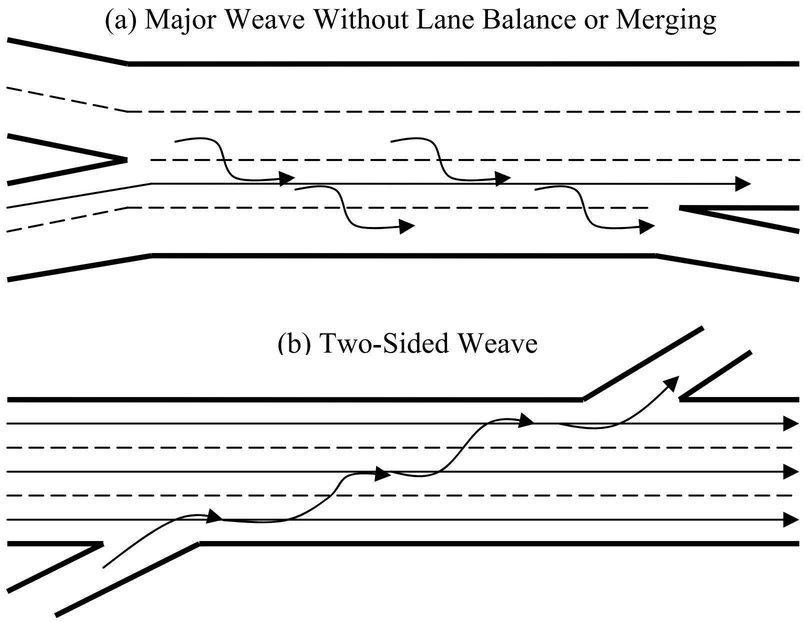


Figure 2.4 Type C Weaving Sections

As discussed above, since the weaving configuration has influence on lane-changing behavior, operations within weaving section are affected by types of the weaving configuration (*2*). Thus, parameters depending on the weaving configurations are an essential key in the models for analyzing freeway weaving sections provided in Chapter 24 of the HCM 2000 (*2*).

Since the weaving vehicles must completely change lanes within the weaving section boundary from the merge area to the diverge area, the parameter that depends on weaving length is important (*2*). For this thesis, weaving length is defined as between the ramp terminals and the downstream intersection.

While several methods and models have been established to analyze freeway weaving sections, most of these methods and models are not applicable to analyze weaving that occurs in the arterial road between ramp terminals and intersections. Arterial roads tend to have various traffic and geometric conditions that can affect weaving operations unique to arterial road weaving sections.

ARTERIAL WEAVING

This section is divided into two parts. The first part covers the arterial road characteristics provided in the HCM 2000, and the second part of this section provides findings from the previous study analyzing the arterial weaving sections between ramp terminals and downstream intersections.

Arterial Roads

The HCM 2000 states that "in the hierarchy of street transportation facilities, urban streets (including arterials and collectors) are ranked between local streets and multilane suburban and rural highways (*2*)." The difference for street transportation facilities is generally determined by the following three factors (*2*):

- Street function;
- Control conditions; and
- Character and intensity of roadside development.

The primary function of arterial streets is to serve longer through trips (*14*). Based on the primary function of serving the through movements along arterial roads, the arterial road level of service is determined. This operating level of service is usually determined by the average travel speed for through vehicles along arterial roads. The travel speed on arterial roads is influenced by the following three factors (*2*):

- Arterial road environment;
- Interaction among vehicles; and
- Traffic signal control.

The arterial road environment is related to the geometric characteristics of the facility and the character of roadside activity (*2*). The interaction among vehicles is affected by three main factors: traffic density, type of vehicles, and turning movements. These factors also affect the operation of vehicles at intersections and between signals along the arterial road (*2*).

Traffic signal control has the largest impact on operations of arterial section. The capacity of the arterial road is related primarily to traffic signal characteristics as well as geometric characteristics (*2*). Since the geometric characteristics are fixed in the short term and the geometrics can be improved only by initiating construction, traffic signal is installed for using efficiently the same space by allocating time among conflicting traffic movements. The arterial road operation can be impacted by the following effects of traffic signals (*14*):

- Number of vehicles arriving on red light;

- Quality of progression; and
- Average control delay.

The average control delay is defined as the portion of the total delay that is attributed to traffic signal operation (*2*). The total delay includes time to approach and enter a signalized intersection, and the control delay includes time to decelerate, move up into the queue, stop, and accelerate.

Previous Studies on Arterial Weaving

A study conducted by Lloyd (*8*) replicated on arterial weaving section between a ramp terminal and a downstream intersection using the TRAF-NETSIM computer simulation model. A purpose of this study was to gain insight into the variables that affected the arterial weaving operations and to assess the applicability of TRAF-NETSIM to analyzing arterial weaving. The following variables indicated in the study conducted by Lloyd appeared to affect the operations of arterial weaving sections (*8*):

<u>Progression</u>: The progression between signals of the ramp terminal and the downstream intersection was found to affect the operation of the arterial weaving section (*8*). The study conducted by Lloyd used the two offsets, and the differing offsets resulted in statistical differences in speeds and delays for both weaving and non-weaving vehicles.

<u>Link Length (from Ramp Terminal to Downstream Intersection)</u>: The link length appeared to affect the operations within the arterial weaving section that was studied (*8*).

Since the link length was associated with the effective weaving area, the link length affected the weaving vehicles attempting to cross the arterial road.

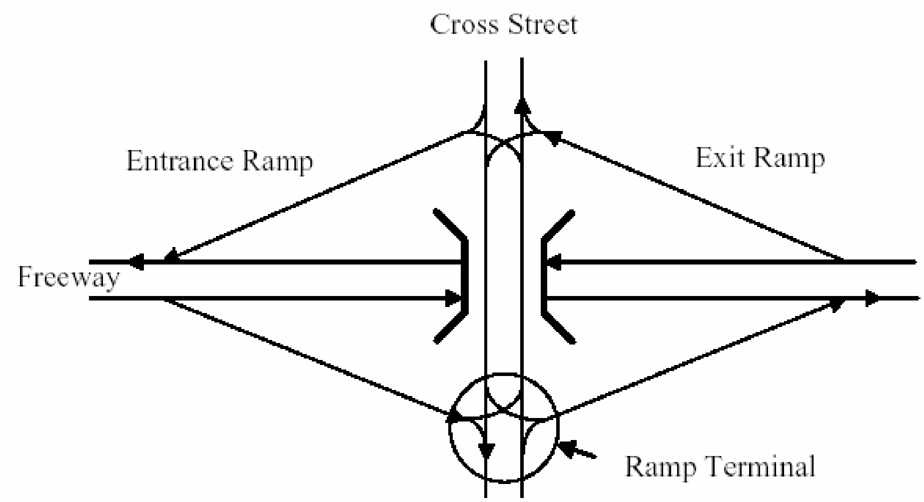
Number of Lanes on Weaving Section: The number of lanes was found to impact the operations of the arterial weaving section (*8*). Since the number of lanes was used as a parameter for calculating weaving and non-weaving speeds of freeway weaving sections (*2*), the number of lanes was also needed to evaluate its effects on the arterial weaving section. However, the results of the study examined by Lloyd indicated that the number of lanes did not appear to affect the operations of the arterial weaving section (*8*).

Total Volume per Lane: Lloyd stated that the total volume affected delays and the number of lane changes made within the arterial weaving section (*8*). Since the number of acceptable gaps decreased as total volumes increased, the right turning vehicles at the ramp terminal had to wait longer to enter the arterial. The results provided by Lloyd revealed that the decrease in acceptable gaps made the weaving vehicles more difficult to complete their desired maneuvers (*8*).

DIAMOND INTERCHANGE

This section provides common geometric configurations of diamond interchanges and signal control strategies for diamond interchanges. Figure 2.5 shows diamond interchanges with and without frontage roads.

(a) Without Frontage Roads



(b) With Frontage Roads

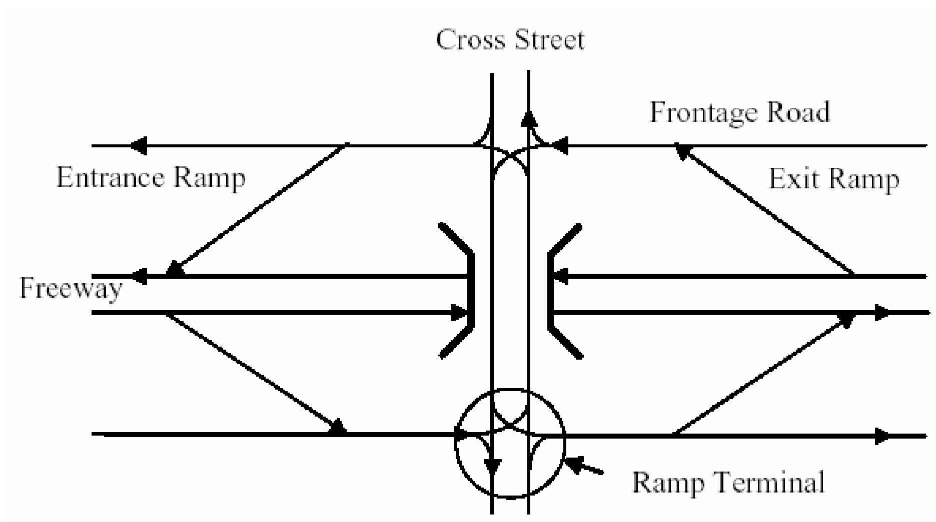


Figure 2.5 Diamond Interchange (*6*)

Configurations

As shown in Figure 2.5, a basic diamond interchange is formed when only one connection is provided for each freeway entry and exit, with one connection per quadrant (*2*), and this configuration may or may not include frontage roads.

There are various diamond interchanges, and the diamond interchanges are usually classified by the spacing of the ramp terminals. The typical diamond interchanges are (*2*):

- Conventional diamond interchanges providing a ramp spacing of 790 ft or more between the two ramp terminals;
- Compressed diamond interchanges having ramp spacing of 395 ft to 790 ft; and
- Tight urban diamond interchanges having ramp terminals spaced less than 295 ft.

Signal Control for Diamond Interchanges

The ramp terminals of diamond interchanges are commonly controlled by traffic signals when high travel volumes occur within the interchange. Since traffic signals of the two ramp terminals are closely spaced within the diamond interchange, special signal phase plans and timings are coordinated to allow for efficient traffic flow through the interchange. In 1961, Capelle and Pinnell identified the following two main objectives of diamond interchange signal control (*15*):

- Separation of all high-volume conflicting movements within the diamond interchange area; and
- Minimization of the number of vehicles stored between the two ramp terminals.

The ramp terminals of a diamond interchange should be controlled together by using either a single controller or two interconnected controllers to achieve these two objectives, as failure to do so could lead to operational problems (*15*). Figure 2.6 shows six signal phases that usually control the various movements at a diamond interchange.

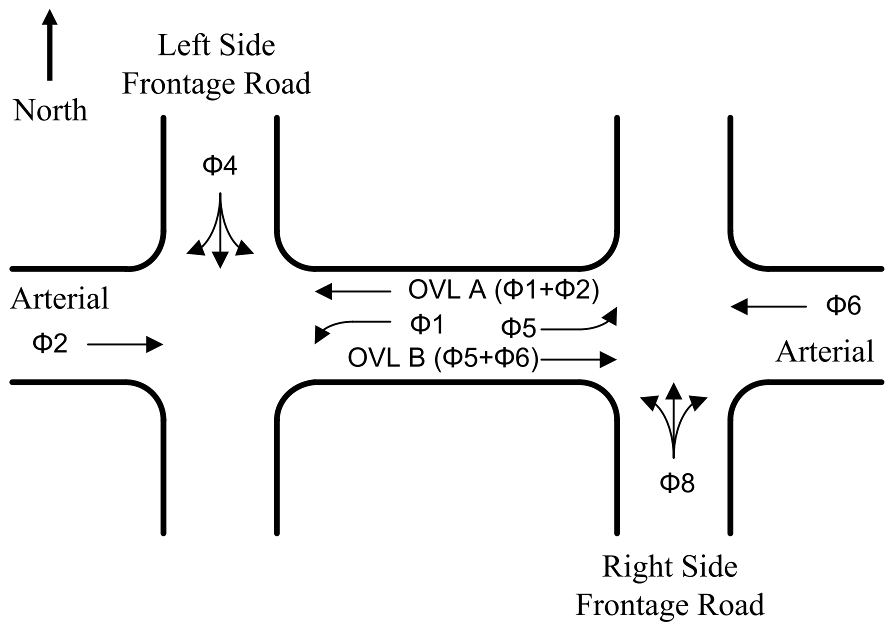


Figure 2.6 Diamond Interchange Signal Phases (*16*)

By convention, Φ2 and Φ6 are defined as the inbound arterial phases on the arterial road (*16*). Since there are no left turns on the exterior movements along the arterial road, two phase overlaps are found within diamond interchanges: Overlap A

(OVL A: Φ1+Φ2) and Overlap B (OVL B: Φ5+Φ6) (*16*). The basic signal control strategies for diamond interchanges are (*2*):

- Three-phase control;
- Four-phase control; and
- Flexible phasing control.

Flexible Control Phasing

Flexible control phasing plan is used at many diamond interchanges by using three basic phases at each intersection. Figure 2.7 illustrates these possible phases that can be used at each intersection, especially at the left side intersection. Under flexible control phasing, the three phases for each intersection can be combined in any order and with any internal offset. Munjal (*17*) has described the phasing patterns by whether the internal left turn phase, Φ1 or Φ5, *leads* or *lags* the exterior through phase, Φ2 or Φ6. Table 2.1 shows all of the possible signal phase sequences.

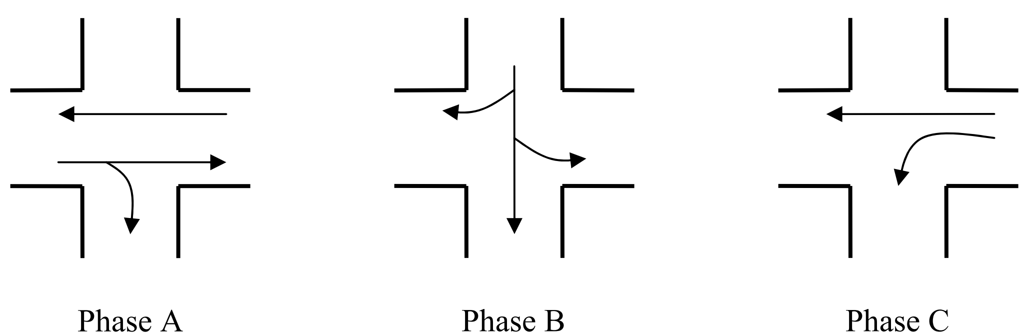


Figure 2.7 Three Phases at Left Side Intersection (*18*)

Table 2.1 Flexible Diamond Interchange Phase Plans (*17*)

	Left Phase Order	Right Phase Order	Phasing Description
1	ABC	ABC	Lead-Lead
2	ACB	ABC	Lag-Lead
3	ABC	ACB	Lead-Lag
4	ACB	ACB	Lag-Lag

Three-phase and four-phase patterns are special cases of flexible control phasing (*18*). Lag-lag phasing of flexible control is a three-phase pattern, and lead-lead phasing of flexible control is the same pattern as four-phase with two overlaps.

Since three-phase and four-phase controls sometimes cause too much congestion because of short ramp spacing, lag-lead or lead-lag phasing is used to reduce the problems. Lag-lead phase sequencing was found to control the two ramp terminals of the diamond interchange that was studied in this thesis.

Internal Offset

All of the possible signal phasing sequences that were discussed earlier can be used with various internal offset between the two intersections from zero to one cycle length (*18*). The HCM 2000 defines that "an offset is the difference, in seconds, between the start of green time at the two signalized intersections of a diamond interchange; it is used to coordinate the through traffic passing through the internal link (*2*)." In this thesis, the offset is defined as the time difference in seconds between the start of phase B on the left side ramp and the end of phase B on the right side ramp. The main advantage of the internal offset is:

- To minimize queuing in the interior of interchange; and
- To provide a green signal at the far side of the interchange for driver expectancy.

When cross street left turns are heavy or storage space is small, it is especially helpful to minimize queued vehicles in the interior of interchange. Since the internal offset always provides a green signal at the far side of the interchange to all movement except U-turns, it is good for driver expectancy (*19*). The internal offset between the two ramp signals is selected to be the same as two seconds less than the travel time (*16,18*). Messer provided the following equation to calculate the internal offset (*16*):

$$\theta_{ij} = T_{PR} + \sqrt{\frac{2S}{a}} - 2 \qquad (3)$$

where:

θ_{ij} = Internal Offset for through movement at intersection i and j (sec);

T_{PR} = Perception-reaction time (sec: typically 0.5 sec);

S = Average running speed on the surface street (fps); and

a = Driver acceleration (fps^2: typically 4.44 fps^2)

COMPUTER SIMULATION

Since time and cost are usually restricted for the collection of field data at every possible weaving configuration, computer simulation models are used to augment the field data. Several researches (*4,8,20*) have been conducted to analyze both freeway and arterial weaving sections using the computer simulation models.

Lloyd investigated the use of the TRAF-NETSIM model to analyze arterial weaving sections, and the results of the study conducted by Lloyd indicated that "TRAF-NETSIM visually appeared to simulate the arterial weaving section very well with its microscopic simulation (*8*)." Link specific of TRAF-NETSIM is a useful tool for the examination of the effects of changing various inputs in a particular manner (*8*).

CORSIM computer simulation model is the latest release of the well-known TRAF-NETSIM (*8*) model. CORSIM, combining the previous NETSIM traffic network simulator with the FREESIM freeway simulator, is one of the most flexible microscopic traffic simulators. The CORSIM (*10*) microscopic traffic simulation model is used for this thesis, and CORSIM provides several measures of effectiveness (MOEs) such as travel time and delay that need to be compared to measured field data.

In this thesis, CORSIM modeled various traffic and geometric conditions using an input file. Table 2.1 lists CORSIM record types that were used for coding the various conditions into the CORSIM model in this thesis.

Table 2.2 Record Type and Description Used in CORSIM (*21*)

Record Type	Description
00 – 05	General information such as run title, run identification, time period specification, and reports.
11	Link description such as number of lanes, link length, nodes where traffic enters and leaves, and free-flow speed.
14	Lane alignments for aligning lanes with lanes on left, diagonal, right, or through receiving link.
21	Surface street turn movements to specify turn movement percentages from current link.
22	Conditional turn movements to define discharge turn percentages that are conditioned on the basis of entry movement.
35 – 36	Sign or pre-timed signal control timing to define any traffic control that is present on networks.
50	Entry link volumes to describe the volume entering networks.
81	Lane-change parameters that should be input to specify lane changing behavior and driver characteristics

SUMMARY

Most research has been conducted for freeway weaving sections, so this literature review has presented the most prevalent methodologies that are used for freeway weaving analysis. Methodologies described previously do not appear to be appropriate for the use in arterial weaving analysis. Therefore, it was observed that there was no standardized methodology to analyze sections such as an arterial road between an interchange ramp terminal and the next downstream intersection.

In the previous study examined by Lloyd (*8*), the variables and parameters that influence the operations of an arterial weaving section between a ramp terminal and a downstream intersection have been discussed using the TRAF-NETSIM computer simulation model. He identified progression, link length between a ramp terminal and downstream intersection, number of lanes on the arterial weaving section, and total volume per lane as the variables affecting the operation of arterial weaving sections. However, he did not determine the effect of weaving maneuvers on the operations of the free right-turn lane at the ramp terminal if the ramp terminal was closely followed by the next downstream intersection with respect to the variables identified.

Lloyd investigated the use of the TRAF-NETSIM model to analyze non-freeway weaving sections such as arterial roads, and the results indicated that “TRAF-NETSIM appeared to simulate the arterial weaving section very well (*8*).” Its successor CORSIM modeled various traffic and geometric conditions in this thesis.

CHAPTER III

STUDY METHODOLOGY

The objectives of this research were to evaluate free right-turn lane operations resulting from vehicles weaving from an exit ramp to a downstream signalized intersection, and to determine delay caused by weaving vehicles stopping on a free right-turn lane. This chapter provides a detailed description of the methodology to evaluate arterial weaving operation. The focuses of the study are a model that can be used to predict the free right-turn lane delay experienced by the stopping weaving vehicles under various traffic and geometric conditions and models that can predict arterial weaving flow conditions based on traffic, geometric conditions. Figure 3.1 presents the outline of the research methodology. This chapter is divided into the following sections: data collection plan, computer simulation development and calibration, model formulation, and model validation.

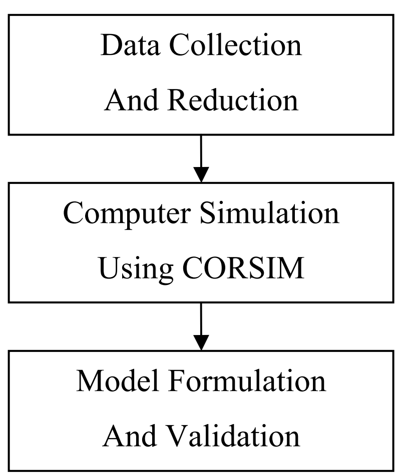


Figure 3.1 Research Methodology Flow Chart

DATA COLLECTION PLAN

The objective of the analytical model developed in this study is to predict the operations and delay of free right-turn lane under various weaving conditions. Field data were collected to analyze the operation of weaving maneuvers between a ramp terminal and a closely spaced downstream intersection, and also to calibrate the computer simulation and test the validity of this model. The field study involved observing an actual arterial weaving and free right-turn lane operations in the field.

Study Site Selection

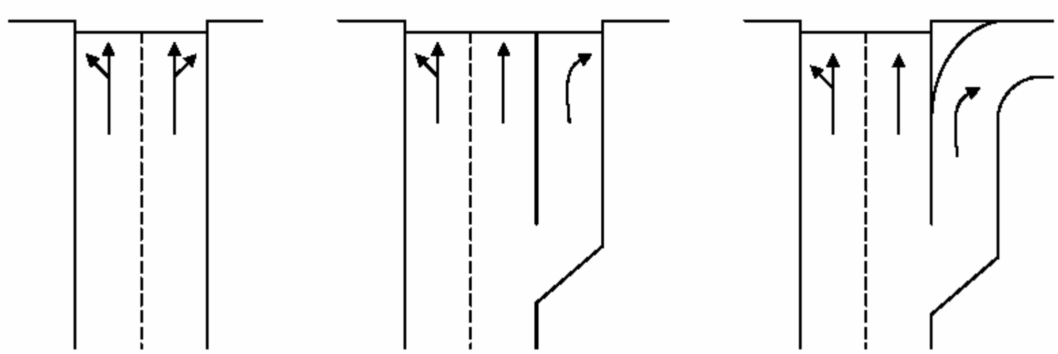
The arterial segment between a diamond interchange and the next downstream intersection was used as a study site for this research. This section of roadway was selected based on the following geometric and operational characteristics:

- Relatively close distance between an interchange ramp terminal and the first downstream intersection;
- A free right-turn lane that is not under signal control at the ramp terminal;
- An auxiliary lane for right-turn movements on the departure leg;
- Heavy exit ramp right-turn volumes destined to turn left at the next downstream intersection; and
- A weaving section with an auxiliary lane.

A large number of weaving vehicles exiting from the ramp terminal and desiring to turn left at the first downstream intersection has a more detrimental effect on the operations of a free right-turn lane on a weaving section than a small number of weaving vehicles. Therefore, a site that experienced heavy exit right-turn volumes turning left at the downstream intersection was selected for this study. This site experienced great turbulence in the area between the exit ramp and the first downstream intersection.

During the process of selecting the study site, it was determined that a site that fully satisfied the criteria for this study would be difficult to find. This difficulty was due to the fact that most exit ramps for right turns at a diamond interchange are configured with an exclusive right-turn lane. As Figure 3.2 illustrates, the following three geometric designs at ramp terminals may be considered for right-turn movements:

- Shared right-turn lane;
- Exclusive right-turn lane; and
- Free right-turn lane.



(a) Shared Right-Turn Lane (b) Exclusive Right-Turn Lane (c) Free Right-Turn Lane

Figure 3.2 Right-Turn Lane Configurations at Ramp Terminals

The chosen site was FM 60 (University Drive) between TX 6 (East Bypass or Earl Rudder Freeway) and Glenhaven Drive. This study site is illustrated in Figure 3.3.

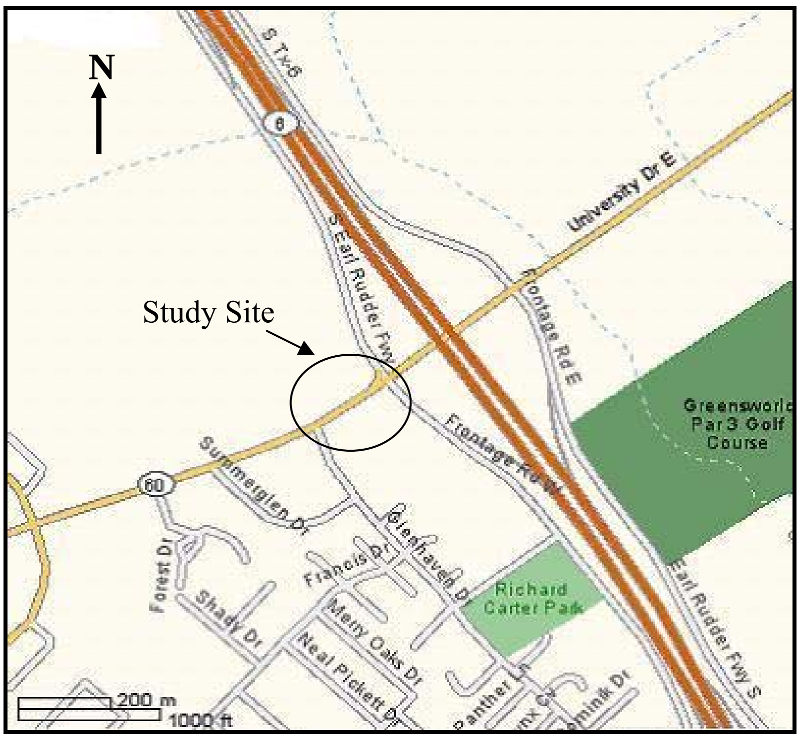


Figure 3.3 Study Site

Data Collection Methods

Fourteen hours of data were collected using video recording equipment at the study site. All data were collected during weekday periods between 7:45 am and 2:30 pm. Five hours of A.M. volumes, three hours of noon volumes, and six hours of P.M. volumes were collected in order to include the hours of peak and off-peak traffic. Data were not collected during inclement weather or unusual traffic conditions like a traffic accident. The volume ranges collected at the study site are shown in Table 3.1.

Table 3.1 Arterial Road Weaving Study Site

Time Period	Arterial Road Volumes		Exit Ramp Volumes		Weaving Volumes	
	Low	High	Low	High	Low	High
	(vph)		(vph)		(vph)	
7:45 - 9:15 A.M.	656	1568	86	228	32	108
10:30 - 11:30 Noon	464	668	65	102	16	60
12:30 - 2:30 P.M.	564	980	79	123	12	92

One video camera was used to record the operation of the free right-turn lane and arterial weaving maneuvers in the weaving segment. This video camera captured the movement of each vehicle within the weaving section. This weaving segment was defined as the area on the arterial road between the physical gore of the ramp terminal and the stop line of the next downstream intersection. Figures 3.4 and 3.5 show the data collection equipment setup and video footage at the field study site, respectively.

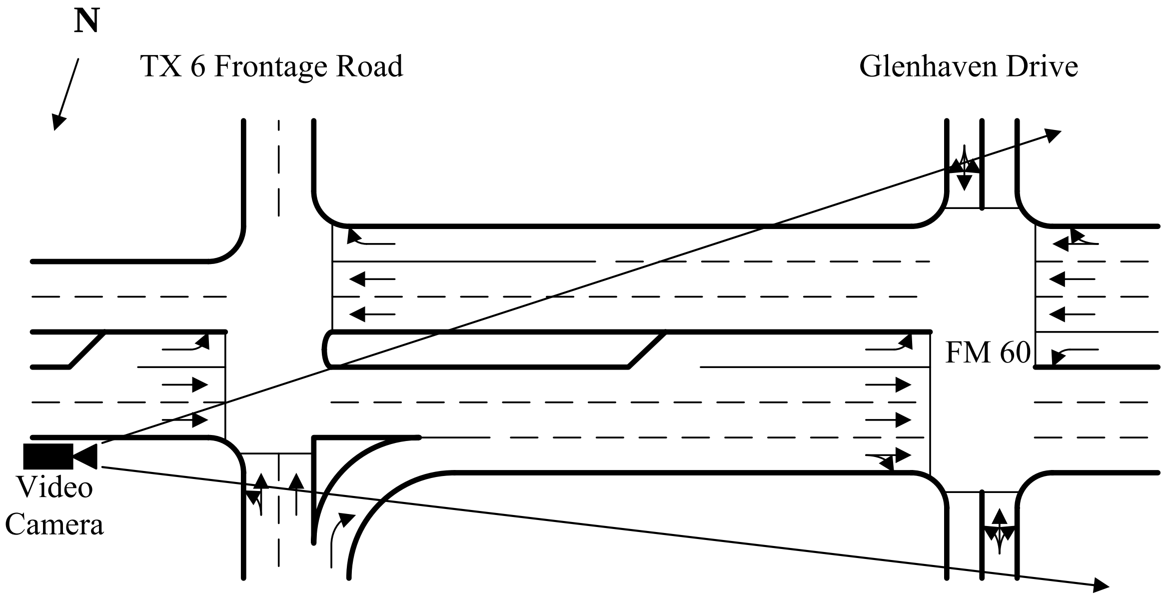


Figure 3.4 Data Collection Setup

Figure 3.5 Video Footage, Westbound FM 60 (University Drive)

DATA REDUCTION PROCEDURE

This section provides a description of the procedure for reducing the videotaped weaving data. Two sheets were used for the data reduction: a volume log for the traffic volumes and queue lengths for each tape, and a weaving log for each weaving maneuver. These sheets and the directions (*22*) for the sheets can be found in Appendix A.

Observation of Volume for Each Movement

The video tapes from the study site were initially viewed to determine through volumes, free right-turn volumes, and weaving volumes. These data were recorded on the volume log sheet. The volume log sheet is divided in to two sections. One section was for the interchange data (in this case, the interchange terminal for FM 60 and the southbound frontage road of TX 6), and the other section was for the downstream intersection data (in this case, the intersection of FM 60 and Glenhaven Drive).

The volumes were recorded for each interchange signal cycle, and then the data were entered into a computer spreadsheet. The number of vehicles making an illegal right-turn maneuver from the southbound frontage road's signalized through lanes were also recorded. The fifteen minute volumes were calculated in the spreadsheet, and these volumes were multiplied by a factor of 4 to convert the volumes to hourly flow rates.

Because vehicles were continuously making the free right turn maneuver without being affected by the interchange terminal signal, these vehicles were counted even when the signal for through traffic was red. The start time of weaving vehicles exiting from the ramp terminal was considered complete when the vehicle's front tires crossed the painted crosswalk line on the free right turn lane. The number of vehicles successfully making the weaving maneuver was also recorded. The weaving vehicles were counted on the intersection signal cycle when the weaving vehicles made a left turn at the downstream intersection. The number of vehicles making an illegal right-turn maneuver was also recorded, but these vehicles were disregarded because the percentage of the illegal right-turn vehicles was very small (five illegal right-turn vehicles out of 5782 total right-turn vehicles).

Observation of Weaving Maneuvers

Data were recorded for vehicles successfully completing the weaving maneuver starting in the free right-turn lane and ending in the exclusive left-turn lane (see Figure 3.6). If there was no queue in the left-turn lane when the weaving vehicle entered it, or if there were moving vehicles that did not force the weaving vehicle to stop, the weaving maneuver was considered complete when all of the vehicle's tires had crossed the solid white line. If there was a queue, the weaving maneuver was considered complete when the vehicle stopped behind the queue. The weaving vehicles were classified as passenger cars or trucks. Since the portion of trucks was very small, the effects of the trucks were not considered (nine trucks out of 704 total weaving vehicles).

Queue lengths at the downstream intersection were recorded to determine the effect of queue lengths on the weaving maneuver. The lengths of the queues in each intersection approach lane (numbers one through three in Figure 3.6) were recorded when the weaving vehicle was inside that lane. The number of queued vehicles in front of the weaving vehicle in the left-turn lane was recorded only when the weaving vehicle was forced to stop.

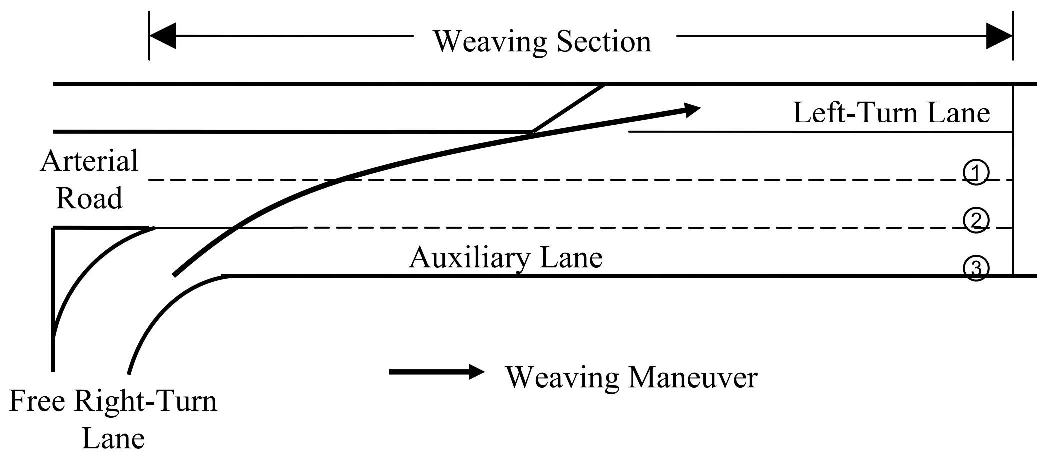


Figure 3.6 Successful Weaving Maneuver

COMPUTER SIMULATION PROCEDURE

The purpose of computer simulation was to augment the field data. Time and cost constraints prohibited the collection of field data at every possible configuration between a ramp terminal and the next downstream intersection. Thus, a wider range of scenarios were investigated by using the computer simulation, and model was developed based on simulation results. The field data was used to calibrate and validate the developed models.

Microscopic Simulator

The CORSIM (*10*) microscopic traffic simulation model was used for the analysis. CORSIM is the latest release of the well-known TRAF-NETSIM (*9*) model, which has been shown to be a good representation of real traffic flow, and to meet all of the following criteria: credibility, applicability, flexibility, and ease of application (*23*, *24*). This microscopic simulator forms part of the Traffic Software Integrated System (TSIS), a user-friendly, graphical user interface that supports CORSIM and its output processor, TRAFVU (*25*). The TRAFVU program graphically shows all of the simulated vehicles moving through the network and provides tools to extract measure of effectiveness (MOEs).

CORSIM consists of the previous NETSIM traffic network simulator with the new FREESIM freeway simulator (*10*). For this study, the NETSIM simulator was used because the environment being modeled was better represented as an arterial network rather than a freeway system.

The environment to be modeled in CORSIM was entered into the simulator using the TRAFED (*26*) network editor for each scenario that was modeled. This editor allows traffic engineers to quickly and easily layout and build traffic networks.

Calibration Process

The purpose of calibrating the computer simulation is to ensure that the simulation closely matched what is observed in the field. The basic method for calibration was to compare the results produced by the simulation to equivalent measures that are found in the field. The simulation is then used to analyze a weaving section between a free right-turn lane and a downstream intersection with different characteristics from the field sites. It was the main idea of model calibration that the simulation can accurately represent other scenarios if it can accurately reproduce the conditions measured in the field (*27*).

Three time periods were chosen for calibrating the simulation. Ranges of arterial volumes and free right-turn lane volumes were offered during these three periods. The time periods used to calibrate the model are listed in Table 3.2.

Table 3.2 Time Periods Used to Calibrate the CORSIM Simulation

Time Period	Arterial Road Volume (vph)		Exit Ramp Volume (vph)		Weaving Volume (vph)	
	Low	High	Low	High	Low	High
7:45 - 8:00 A.M.	1272	1568	218	228	76	108
10:45 - 11:15 Noon	528	744	72	102	20	56
12:50 - 1:20 P.M.	840	1164	103	123	24	92

A number of performance measures for each link in the network are provided in CORSIM. The performance measure that was chosen for calibration was the travel time of the weaving vehicles from the free right-turn lane at the ramp terminal to the left-turn lane at the downstream intersection because the weaving travel time is the most important factor in the weaving maneuvers. In this thesis, travel times for all weaving vehicles and non-stopping weaving vehicles were compared to the weaving travel time measured in the simulation.

A *paired t-test* (*28*) was used to determine if the simulation output was significantly different from the weaving travel time measured in the field. The paired *t*-test is shown in Figure 3.7. If there was significant difference between the simulation and the field data at a 95% confidence level, the input parameters used into the simulator were adjusted. Computer calibration results can be found in Chapter IV.

$$H_o: \quad \mu_d = D_o$$
$$H_a: \quad \mu_d \neq D_o$$

Test Statistic:

$$t = \frac{\bar{d} - D_o}{s_d / \sqrt{n}}$$

Rejection Region: For a specified value of α and $n - 1$ degrees of freedom:

$$\text{reject} \quad H_o \text{ if } |t| > t_{\alpha/2}$$

where

H_o = null hypothesis;
H_a = alternative hypothesis;
μ_d = mean difference;
D_o = selected value;
$\bar{d}$ = sample mean difference;
s_d = sample standard deviation;
n = sample size (pairs);
α = probability of rejecting null hypothesis when it is true; and
$t_{\alpha/2}$ = Student *t* distribution with probability α.

Figure 3.7 Paired *t*-Test (*28*)

In addition to adjusting the simulation parameters, multiple replications of the same simulation must be run, each with different set of random number seeds in order to get an accurate estimate of the expected value of an output variable. Output from CORSIM contains much variation because the simulator is a stochastic model (*29*). The multiple runs were conducted to account for the random variations that were typical in traffic operations. For this study, since the average of the replicated simulation results were judged to accurately represent the equivalent field measurements, three runs were conducted and then the model was considered calibrated.

Development of Scenarios

After the computer simulation has been calibrated, some variables that were identified to have an effect on operations of weaving maneuvers and free right-turn lane operations in the study conducted by Lloyd (*8*) were examined. The variables could be measured in the field. The study on arterial weaving is divided into different scenarios in order to obtain data that could be analyzed.

Scenarios 1, 2, 3, and 4

Scenarios 1, 2, 3, and 4 were simulated under the traffic and geometric conditions presented in Table 3.3. The geometric conditions of distance and number of lanes were the same as the study site conditions. This section focuses on the reasons for the use of each scenario. Figure 3.8 is a schematic representation of the link-node diagram used for computer simulation.

Table 3.3 Input Variable for Scenarios 1, 2, 3, and 4

Input Variables	Value(s) Used
Distance between Two Ramps	1050 ft
Distance between Ramp Terminal and Downstream Intersection	650 ft
Through Volume on Arterial Road	500, 800, 1100, 1400, and 1700 vph
Weaving Percentage	25, 50, and 75 %
Number of Lanes	2 lanes

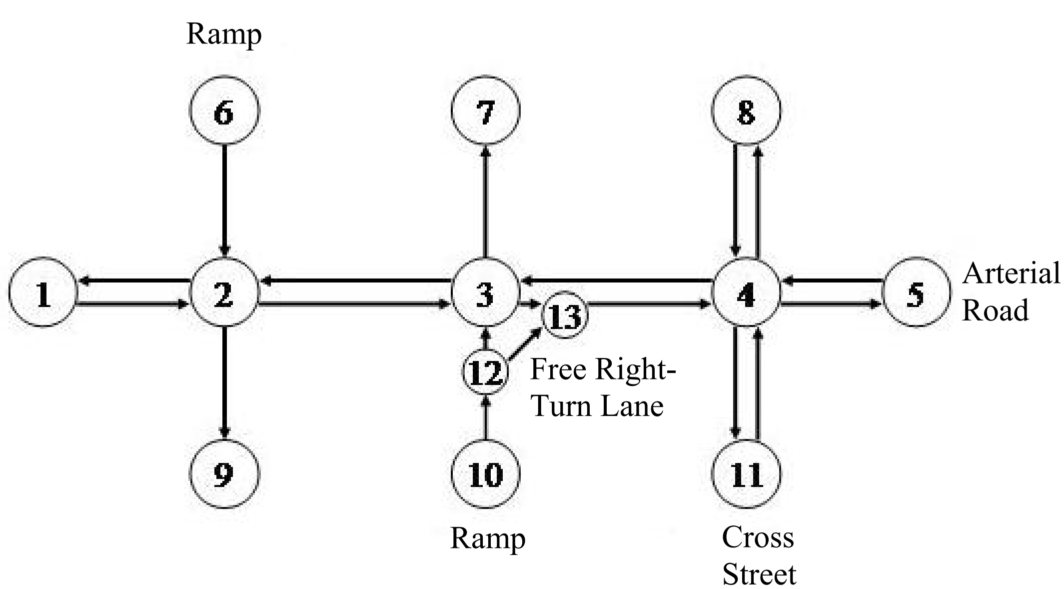


Figure 3.8 Link – Node Diagram for Computer Simulation

Scenario 1 is the operation of the arterial weaving section with 100 percent green for through movement at the two ramp terminals and the downstream intersection. This weaving section is expected to operate like a freeway weaving section. The purpose of this scenario is to establish the performance of the arterial weaving section without any influence from traffic signals. Weaving travel time and delay on the free right-turn lane were then collected and examined.

Scenario 2 included traffic signal states at the two ramp terminals and the downstream intersection. The signals of the two ramps operated under lag-lead flexible control phasing that was used for the diamond interchange at the study site. A g/C ratio of 0.6 for the through movements and a cycle length of 100 seconds were used for the lag-lead phase sequence. Offset of lag-lead sequence was coded by a running travel time between the ramps, so the travel time of 20 sec (for the distance between the ramp terminals of 1050 ft) was used as the offset for this scenario in order to minimize queue lengths on the interior through lanes (*16*). These signal conditions for the two ramp terminals were measured at the study site. This scenario was used to observe the effects that traffic signals have on the weaving vehicles between the ramp terminal and the downstream intersection. The outputs collected include weaving travel time and delay on the free right-turn lane.

For scenario 3, the same conditions as Scenario 2 were used, but an offset of 70 sec between the two ramps' traffic signals was used for this scenario. This offset of 70 sec resulted in longer queue length at the interior through lanes and poor progression between the two ramp signals. In this case, it was measured in CORSIM simulation that the offset of 70 sec caused most through traffic to be queued at the interior lanes. The outputs collected from this scenario are weaving travel time and free right-turn lane delay.

Scenario 4 was conducted to check the impact of an auxiliary lane for right turn traffic movements on the departure leg. This scenario was coded in the computer simulation model with the same conditions as Scenario 2, except that the auxiliary lane on the departure leg was not constructed for right turns in Scenario 4. This scenario also included the YIELD sign on the free right-turn lane. Thus, this right-turn lane design in this scenario can be considered as a merge right-turn lane. Figure 3.9 illustrates the geometric conditions for Scenario 4.

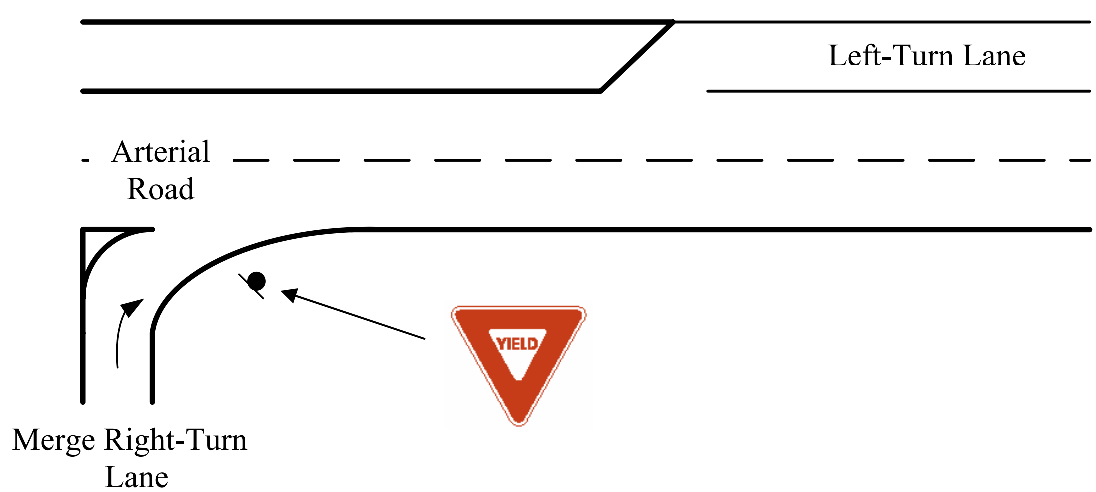


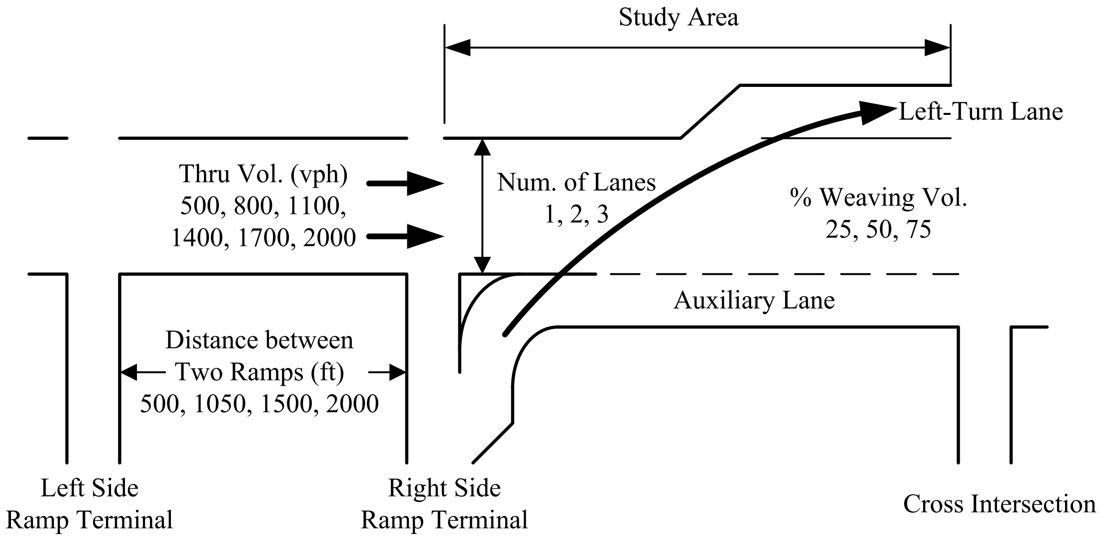
Figure 3.9 Two Lane Arterial Road without Auxiliary Lane (Scenario 4)

Scenarios 1 and 2 were used to observe the influence of the traffic signals at the interchange ramp terminals, and scenarios 2 and 3 were conducted to observe the effects of progression on the arterial weaving movements. Scenario 4 was also compared with Scenario 2 in order to see if there were any differences between delay on the free right-turn lane and the merge right-turn lane. Distinct differences were observed in the outputs measured in each scenario, and these outputs were compared with each other.

Scenarios for Model Development

The next set of scenarios was conducted for development of the model to describe the free right-turn lane operation at the ramp terminal. The variables believed to have influence on the operation of the free right-turn lane were examined. These variables are illustrated in Figure 3.10. The volume variables for the arterial road and the exit ramp included the values measured in the field and used to calibrate the computer simulation.

The geometric conditions such as distance between the two ramps and number of lanes were extended beyond the field ranges to analyze the effect of additional arterial road configurations on the free right-turn lane operations. These additional conditions may be encountered. One-, two-, and three-lane arterial roads with an auxiliary lane on the study area were examined using the computer simulation. All of these cases can be classified as a Type C weaving section since more than two lane changes are required for free right-turn vehicles at the ramp to turn left at the downstream intersection (*2*).



Total Number of Scenarios
$6 \times 4 \times 3 \times 3 = 216$ scenarios

Figure 3.10 Scenarios Simulated in CORSIM

The conditional turning percentage feature of CORSIM can be used to specify origin-destination volumes. The conditional turn movements are provided as percentages of vehicles performing each movement at the downstream node (*26*). This feature also allows all lane distributions to be specified for each simulation scenario (*26*). The specification isolates the effects of different volumes for the same distance between the ramp and downstream intersection on the free right-turn operations, and also isolates the effects of the different distances for equivalent volume conditions (*27*).

Vehicles entering the weaving section were assigned separate turning movements. 85 percent of all vehicles entering from the arterial road (link 3-13) were assigned as through movements, and 5 and 10 percent of them were assigned as right-turn movements and left-turn movements at the downstream intersection, respectively. Since there was auxiliary lane for right-turn movements on the weaving section in all scenarios, 5 percent of the arterial road traffic turning right at the intersection needed to change into the auxiliary lane in the weaving section. These movements were based on field observations that indicated that similar patterns occurred at the field site.

The weaving vehicles entering from the exit ramp terminal (link 12-13) were assigned diagonal movements on the free right-turn lane. All weaving movements were assigned left-turn movements at the downstream intersection. Since the percentage of ramp terminal volume turning left at the downstream intersection was one of the variables, this percentage varied in the different simulation runs. In all cases, the ramp terminal movements that were not assigned to turn left at the intersection were assigned through and right-turn movements at the downstream intersection.

In the case of a one-lane arterial road, only the 500, 800, and 1100 vph arterial road volumes were considered and simulated since other volumes (1400, 1700, and 2000 vph) would result in operations that were over capacity and thus require the addition of another arterial road lane. Similarly, in the case of a two-lane arterial road, the 2000 vph scenario was not simulated.

MODEL DEVELOPMENT

The next step is to use the results of the simulation to develop an analytical model to describe the free right-turn lane operations between the ramp terminal and the next downstream intersection after all of the simulation runs has been completed. The model development process was initiated by listing those variables believed to have influence on the operations of the free right-turn lane and the weaving section. The following variables were included in the model:

- Arterial through volume;
- Free right-turn volume at the ramp terminal;
- Total volume on the weaving section;
- Percentage of ramp terminal volume turning left at the next downstream intersection;
- Distance between the two ramp terminals at the diamond interchange; and
- The number of arterial road lanes.

An average distance of 600 feet between the ramp terminal and the downstream intersection exhibited operational problems under high volume conditions (*30*). Since the link length of the study section was measured as 650 feet (more than 600 feet) and there was not proper field data to calibrate a model with this link length, ramp to intersection spacing was not considered as a variable in the model.

In addition to these explanatory variables, the following response variables were also considered:

- Delay caused by weaving vehicles stopping on free right-turn lane; and
- Travel time of weaving vehicles between the ramp terminal and the downstream intersection.

Based on the results from the computer simulation, plots were drawn to identify the relationship between each explanatory variable and the response variable for each geometric configuration such as the ramp terminal spacing and the number of arterial road lanes.

MODEL VALIDATION

Once the analytical model to predict operations of the free right-turn lane had been developed, the model validation was conducted. The validation process consists of comparing two systems, the simulated and the observed, and checking how one approximates the other. Measures of effectiveness (MOEs) had to be defined before the simulated and the observed data were compared. The data used for validating the model was obtained for a different time period from those used to calibrate the model. Statistical analysis was conducted for comparing the modeled and observed results by using the paired *t*-test explained in Figure 3.7, and then the difference between these two results were checked. Validation results can be found in Chapter IV.

CHAPTER IV

STUDY RESULTS

This chapter documents the results of the investigation into the operations of the arterial weaving section between the ramp terminal and the downstream intersection and the free right-turn lane at the ramp terminal. The results were based on the data collected in the field and obtained from the CORSIM simulation model. This chapter is divided into three major sections to provide the results in an orderly fashion. The first section presents the results from the field data collection and analysis. The second section consists of the results of analyzing the data obtained from the computer simulation program for each scenario. Statistical analyses between these scenarios are also provided in this section. The final section presents the results of the model formulation and validation.

FIELD DATA RESULTS

This section documents the findings obtained in the field for this study. The discussion focuses on results of the field data collection and analysis. These observations help in easily understanding the effect of weaving maneuvers on the free right-turn lane operations in the field.

Field Data Collection

The fourteen hours of data recorded using video recording equipment at the study site were viewed to determine time periods of A.M., noon, and P.M. volumes. These data collection periods experienced peak hour volumes, median volumes, and off-peak hour volumes, respectively, between the arterial road and the ramp terminals. It was also observed for those time periods that a large percentage of right-turn vehicles exiting from the ramp terminal attempted to turn left at the downstream intersection. The observation periods were then divided into five-minute time periods to collect the five-minute origin-destination volumes at the study site, and then these volumes were multiplied by a factor of 12 to determine the equivalent hourly volume.

Several warning signs indicating the exclusive receiving lane were found at the study site. There are two warning signs for indicating merging movements ahead. The *Manual of Uniform Traffic Control Devices* (MUTCD) (*31*) states that "A Merge (W4-1) sign may be used to warn road users on the major road way that merging movements might be encountered in advance of a point where lanes from two separate roadways converge as a single traffic lane and no turning conflict occurs", and "the Added Lane (W4-3) sign should be installed in advance of a point where two roadways converge and merging movements are not required (*30*)." Figure 4.1 illustrates the Merge sign (W4-1) and the Added Lane sign (W4-3).

(a) Merge Sign (W4 – 1)　　　(b) Added Lane Sign (W4 – 3)

Figure 4.1 Warning Signs from the MUTCD (30)

Another common treatment consists of a single-white line between the rightmost arterial road lane and the auxiliary lane for the free right-turn vehicles. The white line is for delineating the separation of traffic flows in the same direction beyond the arterial road/free right-turn lane junction (*32*). It was commonly observed that right-turn drivers crossed the white line if an opening in the arterial road was available. Also, drivers on the rightmost lane of the arterial road rarely slowed down when the right-turn vehicle existed on the free right-turn lane. The various treatments found at the study site are presented in Figure 4.2. It was indicated by the field data that the warning sign and the white line used at the study site did not seem to influence the behavior of drivers as much as the driver's familiarity with the area.

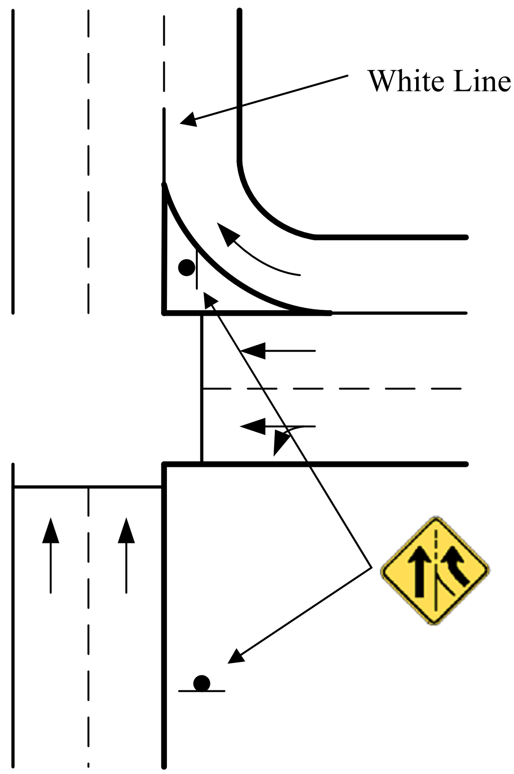


Figure 4.2 Warning Signs Used at the Study Site

Field Data Analysis

In the case of a two-sided weaving configuration (Type C), through traffic flow has influence on the operations of weaving maneuvers. The field data revealed that all of stopping weaving vehicles on the free right-turn lane were observed during green signal for arterial through traffic (Overlap B: Φ5+Φ6). The observation of weaving behavior indicates that several right-turn drivers exiting from the ramp terminal would stop on the free right-turn lane during green signal for arterial through traffic (Overlap B: Φ5+Φ6).

They would wait for sufficient headway between through vehicles on the arterial road so they could safely weave across the arterial road lanes.

Using the data obtained from the field site, the two relationships examined were the effects of arterial through volume on the travel times of all weaving vehicles and non-stopping weaving vehicles. Table 4.1 provides a summary of the average weave travel time of all and non-stopping weaving vehicles for each hourly through volume obtained from the field data.

Table 4.1 Average Weave Travel Time

Through Volume	Average Travel Time of Weaving vehicles	
	All Weaving Vehicles	Non-Stopping Weaving Vehcles
(vph)	(sec)	(sec)
450~550	10.9	10.7
550~650	12.4	11.3
650~750	13.9	12.1
750~850	13.7	12.0
850~950	14.7	12.0
950~1050	13.6	11.7
1450~1550	14.6	11.7

In general, the travel times of all weaving vehicles tend to increase as the through volume increases because waiting and stopping time on the free right-turn lane increased. This is expected because weaving vehicles are affected by conflicting through movements. The travel time of non-stopping weaving vehicles on the free right-turn lane was collected to compare to the overall travel time. As Table 4.1 shows, the travel time of non-stopping weaving vehicles appears to be relatively constant as the through volumes increase. This relationship indicates that the through volumes do not have much influence on the travel time of non-stopping weaving vehicles on the free right-turn lane.

The different travel times between all and non-stopping weaving vehicles may be considered a delay on the free right-turn lane. Figure 4.3 shows the data points and the fit line for the relationship between the arterial though volume and the delay by weaving vehicles stopping on the free right-turn lane. As described by the fit line in Figure 4.3, the free right-turn lane delay tends to increase when the arterial road volume increases.

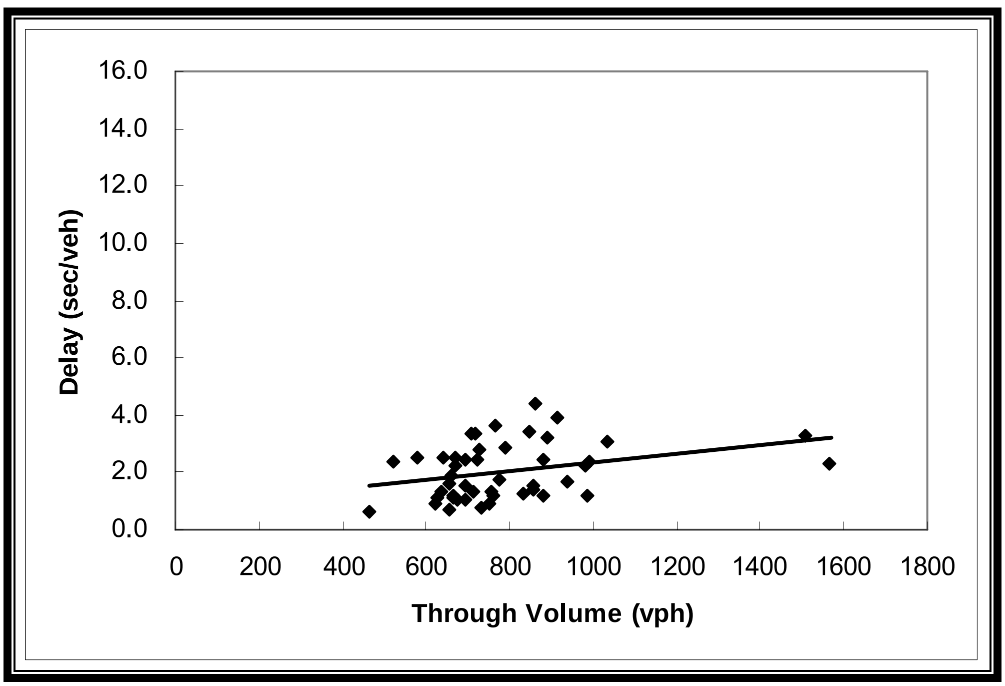


Figure 4.3 Effect of Arterial Through Volume on Free Right-Turn Lane Delay

In the case of this study site, once again, although drivers did not need to stop on the free right-turn lane because of the auxiliary lane for right turns on the departure leg, weaving drivers exiting from the ramp terminal would stop on the free right-turn lane and wait for an opening that would them to weave to the arterial road. In summary, the following preliminary observations were indicated in the field site:

- Travel times of all weaving vehicles increased as the arterial through volume increased;
- Travel times of non-stopping weaving vehicles on the free right-turn lane were relatively constant as the arterial through volume increased; and
- Free right-turn lane delay increased as the arterial through volume increases.

The computer simulation was used to find relationships between other factors and free right-turn lane delay.

COMPUTER SIMULATION RESULTS

As described in Chapter III, the computer simulation model should be calibrated using the field data. The purpose of the computer simulation procedure is to check the relationships between the measure of performance and the possible variables. Two sections are presented in this chapter including the results of computer simulation calibration as well as the computer simulation calibration results.

Calibration of Computer Simulation Model

As discussed earlier in Chapter III, three time periods were chosen to calibrate the computer simulation. These time periods represented the peak hour and off-peak hour traffic demand. Geometric configurations and traffic control signals at the existing study site were coded into the computer simulation. For the A.M. time period, three simulation runs were conducted for three of the five-minute volumes. These five-minute volumes were made up the 15-minute observation period. For noon and P.M. time periods, similarly, six separate simulation runs were performed, one for each of the five-minute volumes during the 30-minute period. In addition, five random number seeds were used to capture some of the random traffic variations. The combination of all conditions resulted in 75 data points (3 volumes x 5 replications + 6 volumes x 5 replications + 6 volumes x 5 replications) for the calibration.

Using the hourly flow rates that were calculated from the five-minute volumes, each computer simulation model ran for a period of one hour. The average travel time of all weaving vehicles and non-stopping weaving vehicles on the free right-turn lane were used as the performance measures for calibration of the computer simulation model.

Default parameters for lane changing behavior and driver characteristics were used for the initial calibration runs. As the next attempt to calibrate the initial simulation runs, the values of the percentage of drivers who cooperate with a lane changer and the distance over which drivers will perform a lane change were adjusted. The percentage of drivers represents drivers who would slow down to allow drivers to change lane in front of them (*24*). Since there were two Added Lane signs on the side of the arterial road before the ramp terminal, most through traffic drivers did not slow down for the merging movement. Thus, the percentage of vehicles that would slow down to allow for a lane changer was decreased from the default of 50 to 20 percent. The value of the lane change distance means the needed distance to determine when the drivers would first initiate a required lane change. This distance was increased from the default of 300 to 450 ft. It improved the degree of agreement between the simulation outputs and the field data to change these two parameters for the lane change behaviors.

After the calibration, the average travel time of all weaving vehicles and weaving vehicles not stopping on the free right-turn lane were close to those values measured in the field data. These average travel times from the results of the computer calibration are listed in Table 4.2.

A paired *t*-test between the two average travel times was conducted using Statistical Analysis Software (SAS). This test procedure shows whether there is any difference between two observations taken under homogeneous conditions (*28*). The travel times measured from the field data and the computer simulation data under the same conditions were analyzed to determine the difference. The results of the paired *t*-test are listed in Table 4.3.

From the results of the paired *t*-test, it was found for each time period, there was no significant difference on the average between the travel times simulated by the computer program and collected from the field data at a 95 % confidence level. Thus, the average results of the computer simulation were close to what was actually occurring at the field site under the conditions simulated.

Table 4.2 Results of the Calibration of the Computer Simulation

Time Period		Average Travel Time (sec)					
		All Weaving Vehicles			Non-Stopping Weaving Vehicles		
		CORSIM	Field	Difference	CORSIM	Field	Difference
A.M.	7:45 to 8:00	15.7	15.8	0.1	11.7	11.8	0.1
Noon	10:45 to 11:15	12.9	12.8	0.2	11.5	11.3	0.2
P.M	12:50 to 13:20	13.9	14.7	0.9	11.8	11.5	0.3

Table 4.3 Paired *t*-Test Results

Travel Time	Calculated *t*-value	Degree of Freedom	Significance value	95% Confidence Interval of the Difference	
				Lower	Upper
All Weaver (A.M.)	-0.22	2	0.85	-0.97	0.88
Non-Stopping Weaver (A.M.)	-0.37	2	0.75	-0.82	0.69
All Weaver (Noon)	0.32	5	0.76	-1.12	1.44
Non-Stopping Weaver (Noon)	-1.64	5	0.16	-1.77	0.39
All Weaver (P.M.)	-1.26	5	0.27	-2.61	0.89
Non-Stopping Weaver (P.M.)	-1.12	5	0.29	-1.23	0.45

Comparison of Scenarios

After the calibration of the computer simulation model, the next step is to analyze the results provided by all of the simulation runs. Various simulation scenarios were coded as described in Chapter III, and each scenario was simulated for a period of one hour.

Once all of the scenarios were simulated, the output needed for this thesis was obtained from TRAFVU. TRAFVU records the delay on the free right-turn lane and the travel time of weaving vehicles on the weaving link. The output data was then imported into a spreadsheet for plotting the graphs for each simulation run.

This section is divided into three sections. The first section presents the results of Scenarios 1 and 2. The second section presents the comparison of Scenarios 2 and 3. The final section provides the analysis of the effect of an auxiliary lane for right turns on the departure leg.

Effect of Traffic Signals

The first analysis was the comparison of Scenarios 1 and 2. Scenario 1 represents the arterial weaving section without the influence of signals at the diamond interchange ramps and the downstream intersection. Scenario 2 includes the traffic signals at the both ramps and the downstream intersection. In the case of Scenario 1, the arterial traffic received 100 percent green at the ramp terminals, as the weaving movements operated like freeway weaving movements.

The upper graph in Figure 4.4 provides the best fit lines for the relationship between arterial road volume and travel time of all weaving vehicles with and without traffic signals. In general, the travel time tends to increase as the arterial through volume increases. The increase in travel time was found to be greater with signals than without signals. In other words, the rate of change of the travel time is greater when the traffic signals are installed on the weaving section. These results indicate that the arterial road volume is more likely to affect the weaving maneuver with the signals and less likely to affect the weaving maneuver without the signals.

The plot of the actual data points resulting from the computer simulation is shown in the lower graph in Figure 4.4. Due to the different percentage (25, 50, and 75 %) of weaving vehicles for the same arterial volume level, there are multiple data points at a particular volume level with and without the traffic signals. This figure shows that the variance in the data points increases when the through volume increases.

Overall, as shown in Figure 4.4, the travel time of all weaving vehicles with the traffic signal is lower at a particular volume level than the travel time without the traffic signal at the same volume level since. Since, in the case of traffic signal usage, most weaving vehicles are not conflicted by the arterial road volume during red signal for the arterial through traffic, average travel time of all weaving vehicles for signal is less than for no signal.

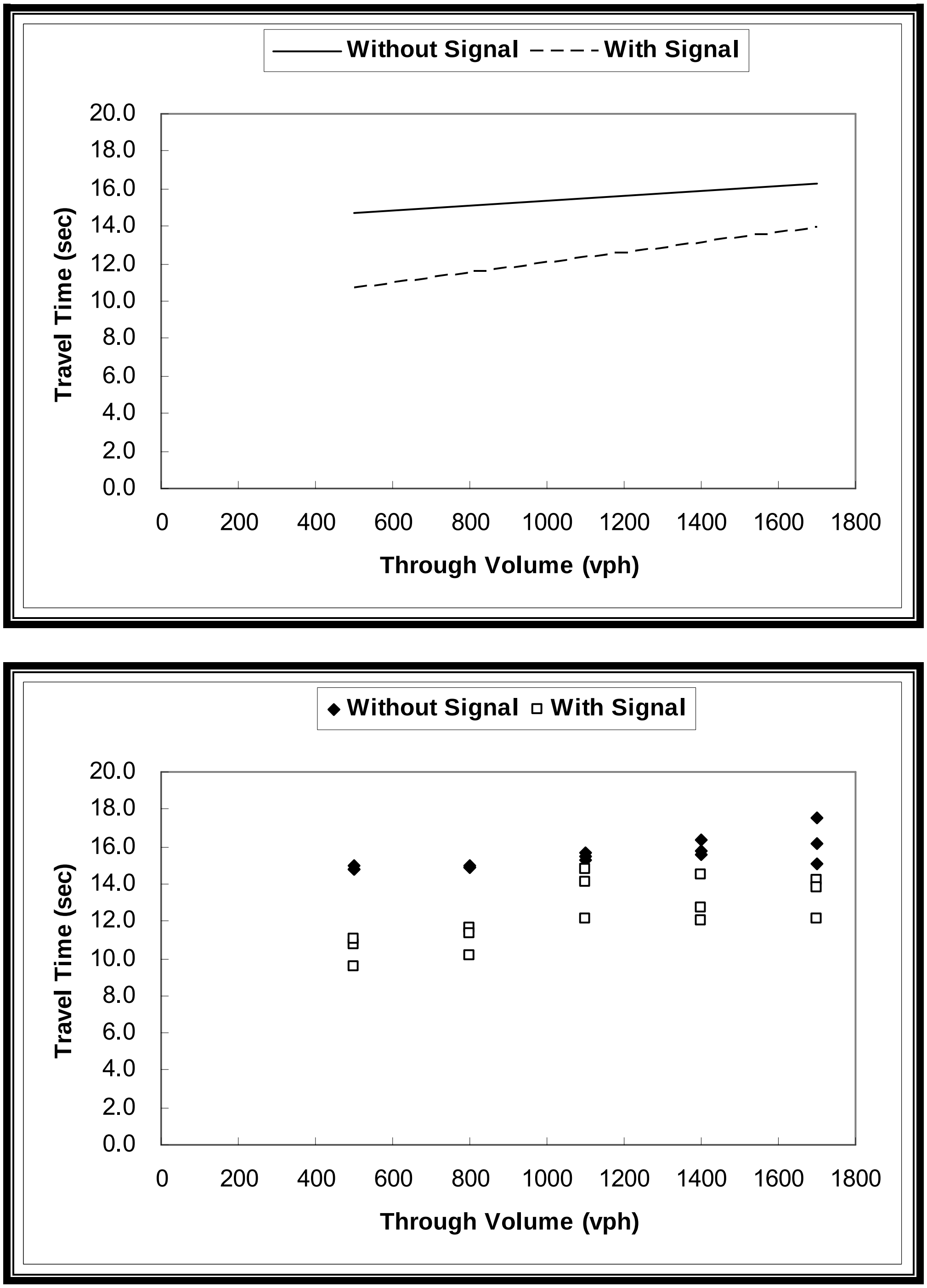
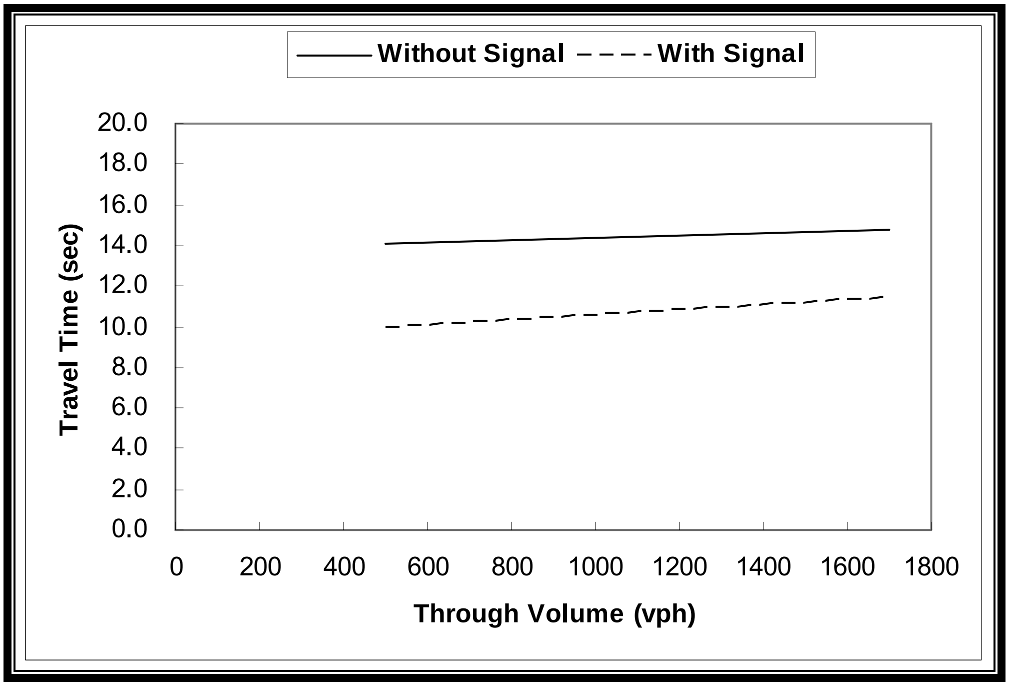


Figure 4.4 Effect of Signal on Travel Time of All Weaving Vehicles

Similar results were found in the relationship between the arterial through volume and the travel time of non-stopping weaving vehicles on the free right-turn lane. Examination of the best fit lines in the upper portion of Figure 4.5 reveals that the travel time increases as the arterial traffic volume increases with and without the signal. However, the travel time of non-stopping weaving vehicles on the weaving section remained relatively constant (within one second) when the arterial road volume increased. Figure 4.5 also indicates that the travel time with the traffic signal is lower than without the traffic signal at the same through volume level. This result reveals influence of the traffic signals on the weaving maneuvers. The lower graph in Figure 4.5 shows the data points obtained from the computer simulation model.

Figure 4.6 illustrates the relationship between the arterial road volume and the delay caused by stopping weaving vehicles on the free right-turn lane. As indicated by the best fit lines in the upper graph of Figure 4.6, in Scenarios 1 and 2, the delay on the free right-turn lane increases as the arterial road traffic increases. The increase in delay was found to be 1.5 seconds greater with traffic signals than without traffic signals. The effect of traffic signals on the free right-turn lane delay is evidenced by the steeper slope for the fit line with signals.

The data points with and without signals are plotted in the lower portion of Figure 4.6. In Scenarios 1 and 2, the data points were concentrated for the lower volumes, but there was more scatter among the data as the through volumes increased. The greater scatter at the higher through volumes might be attributable to an increased number of slower vehicles on the weaving section.



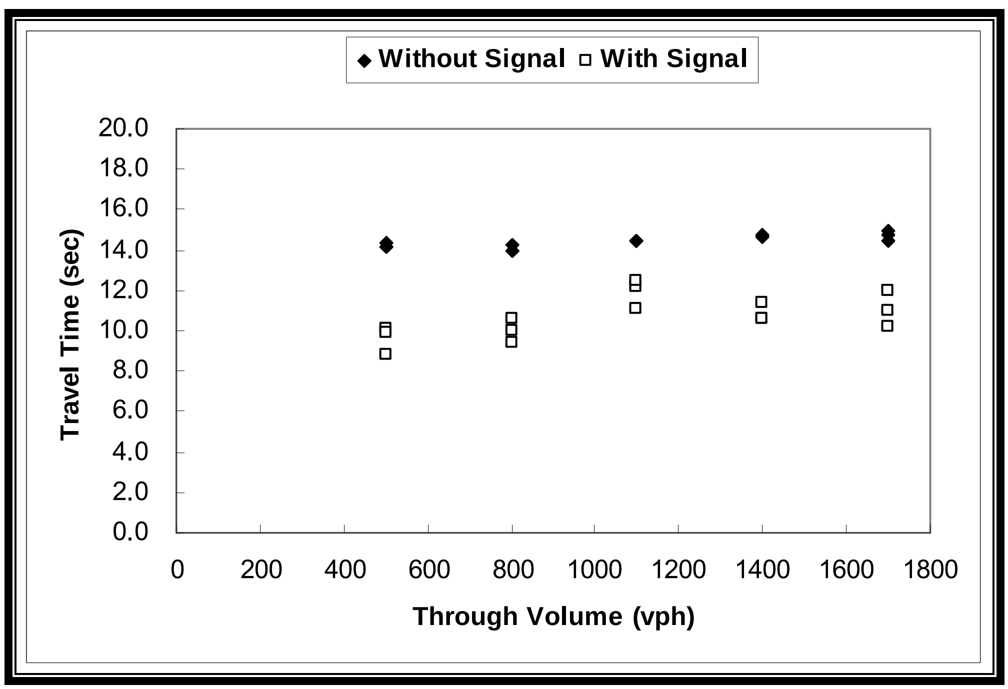


Figure 4.5 Effect of Signal on Travel Time of Non-Stopping Weaving Vehicles

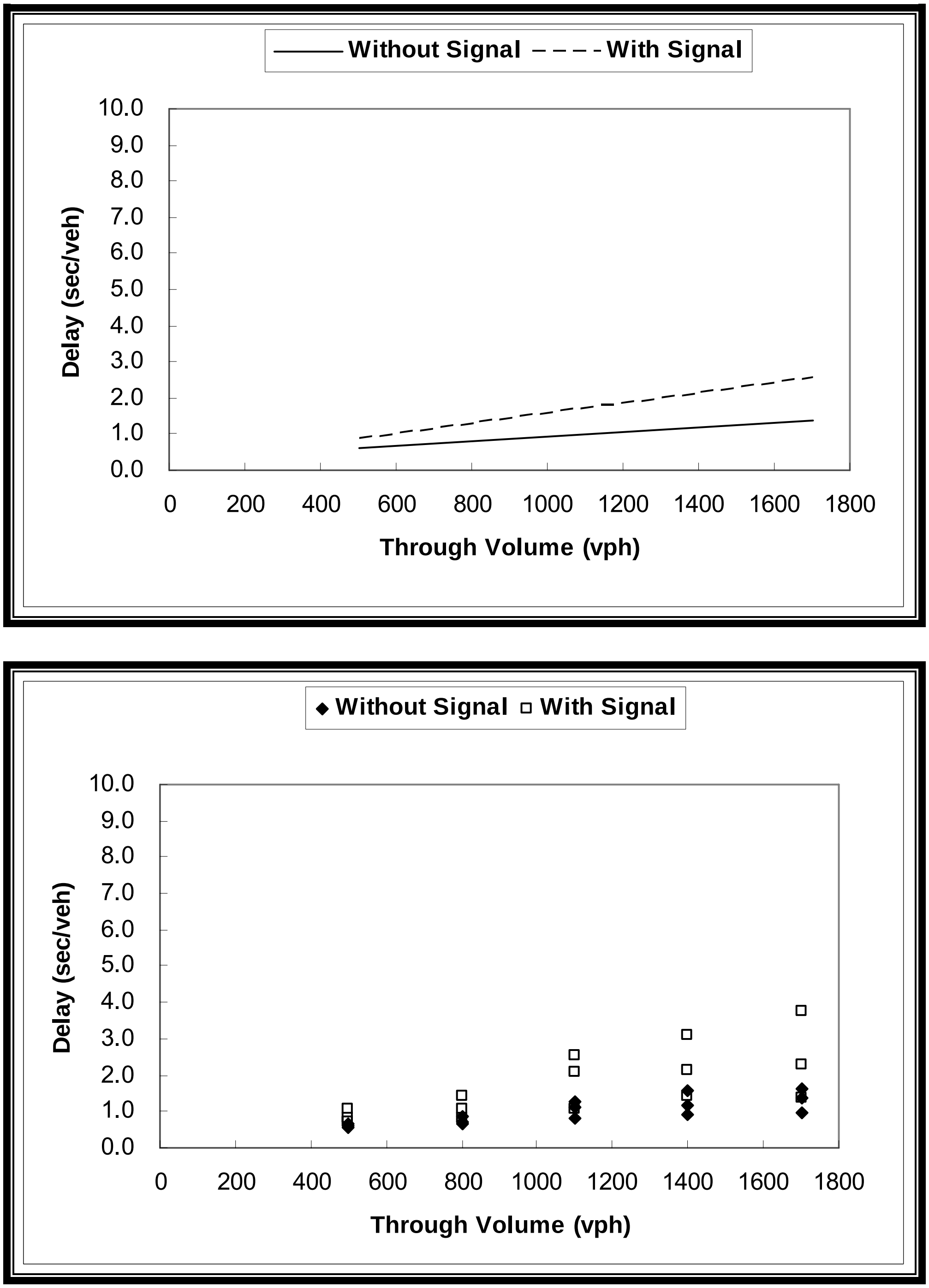


Figure 4.6 Effect of Signal on Free Right-Turn Lane Delay

The paired *t*-test was conducted to determine whether there was a significant difference between outputs for Scenarios 1 and 2. As indicated by the above figures, since the difference between the weaving travel time for Scenarios 1 and 2 is higher than the difference between the free right-turn lane delay for Scenarios 1 and 2, the delay caused by stopping weaving vehicles on the free right-turn lane was used for this *t*-test.

The results of the test for the delay are listed in Table 4.4. The null hypothesis used for the *t*-test was that the average delay between the scenarios was equal. Since the calculated *t*-value was more than the critical *t*-value, the hypothesis was rejected at a 95% confidence interval. Therefore, there is evidence to conclude that mean delay with traffic signals is different from the mean delay without traffic signals. Since the supply of acceptable gaps for weaving vehicles is to be controlled by the traffic signal, the introduction of signals has significant influence on the free right-turn lane delay caused by weaving vehicles.

Table 4.4 Paired *t*-Test Between Scenarios 1 and 2 for Delay

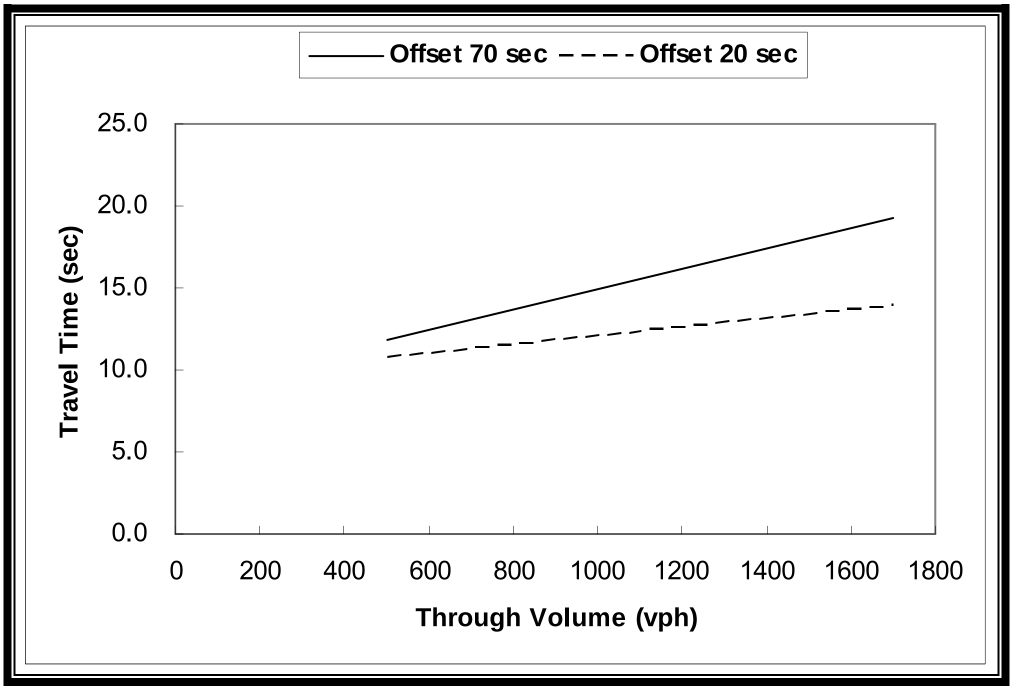
	Scenario 1 (Without Signal)	Scenario 2 (With Signal)
Mean	1.32	1.69
Num. of Sample	42	42
Variance	0.73	0.91
Degree of Freedom	41	
Calculated *t*-value	-4.84	
Critical *t*-value	2.02	
Significance value	0.0	

Effect of Internal Offset Change

The second examination was conducted to check whether different offsets between the traffic signals of the ramp terminals affect the weaving maneuvers. For this examination, the data obtained from the computer simulation for Scenario 2 were compared with the data collected for Scenario 3. These two scenarios represent the same conditions (geometric configuration and signal timing phasing for the two ramp terminals and downstream intersection) measured at the study site. As discussed earlier, the lag-lead phasing sequence was used for the diamond interchange in these scenarios.

However, different internal offsets between the two traffic signals at the ramp terminals were coded for these two scenarios. An internal offset of 20 sec was used for Scenario 2. This offset of 20 sec is the optimal offset for minimizing total delay time at the diamond interchange and queue length on interior lanes at the ramp terminal because this offset is the same as two seconds less than the travel time. An internal offset of 70 sec was coded into the computer simulation for Scenario 3. In Scenario 3, TRAFVU program graphically showed that most through vehicles had to stop for the red right on the interior lanes at the downstream ramp terminal.

The first relationship that was examined was the effect of offset change on the travel time of all weavers in the weaving section. The best fit lines for the relationship between the travel time and the arterial road volume are shown in the upper graph of Figure 4.7. Overall, these fit lines indicate that the travel time increases with arterial through volume in the cases of both 70 and 20 sec offset. It is also revealed by this graph that the travel time of all weaving vehicles on the weaving section is much higher at a



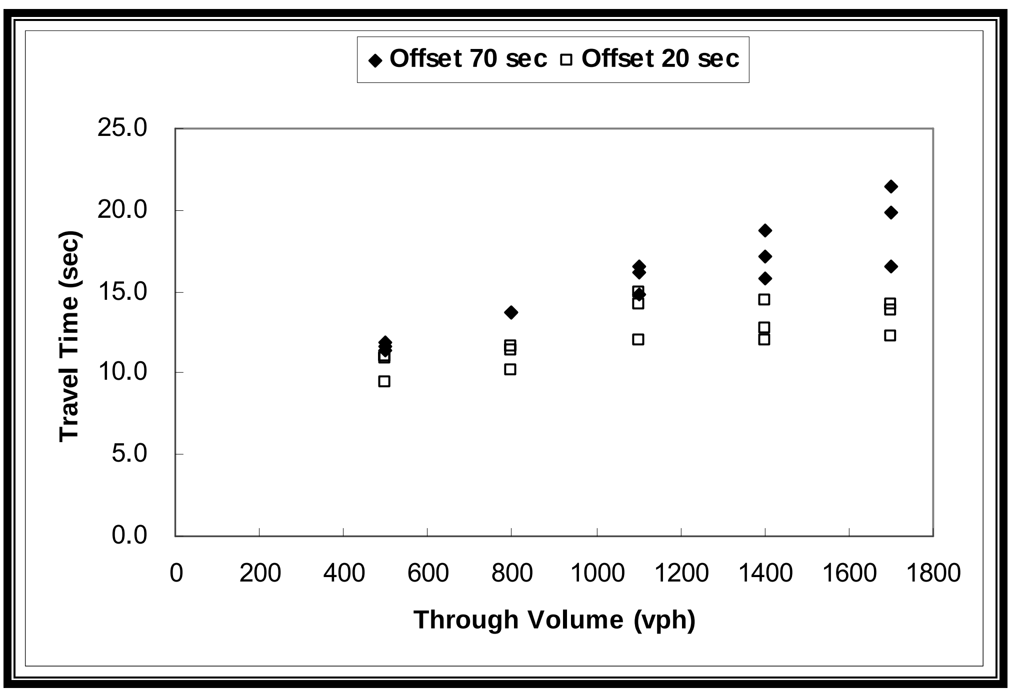


Figure 4.7 Effect of Offset on Travel Time of All Weaving Vehicles

particular through volume with an offset of 70 sec than with an offset of 20 sec. As indicated by the steeper slope for the respective best fit lines, the increase in travel time was 3 seconds greater for the offset of 70 sec than for the offset of 20 sec. In other words, the increase in travel time for the offset of 70 sec is more likely to be affected by the increase in the arterial through volume than for the offset of 20 sec.

This result might occur because higher through volumes caused longer queue length on the interior lanes with the offset of 70 sec causing a poor progression between the two ramp terminals within the interchange. This longer queue resulted in a dense platoon on the weaving section, and the dense platoon affects the weaving travel time.

The bottom portion of Figure 4.7 illustrates that the multiple data points that resulted from the various weaving percentages (25, 50, and 75 %) are more scattered at the higher through volumes than at the lower through volumes. This means that the variance in the data increases for each offset as the arterial through volume increases. The data points at the lower through volumes indicate that the travel times for 70 and 20 sec are close to each other. This outcome at the lower through volume might be due to the short queue length on the interior lanes at the ramp terminal for both offsets of 70 and 20 sec.

The relationship between the travel time of non-stopping weaving vehicles on the free right-turn lane and the arterial road volume is shown in Figure 4.8. The best fit lines in the upper graph of Figure 4.8 indicates that as the arterial through volume increases the travel time of weaving vehicles not stopping on the free right-turn lane also increases for Scenarios 2 and 3. However, the increase in the travel time for Scenario 3 was

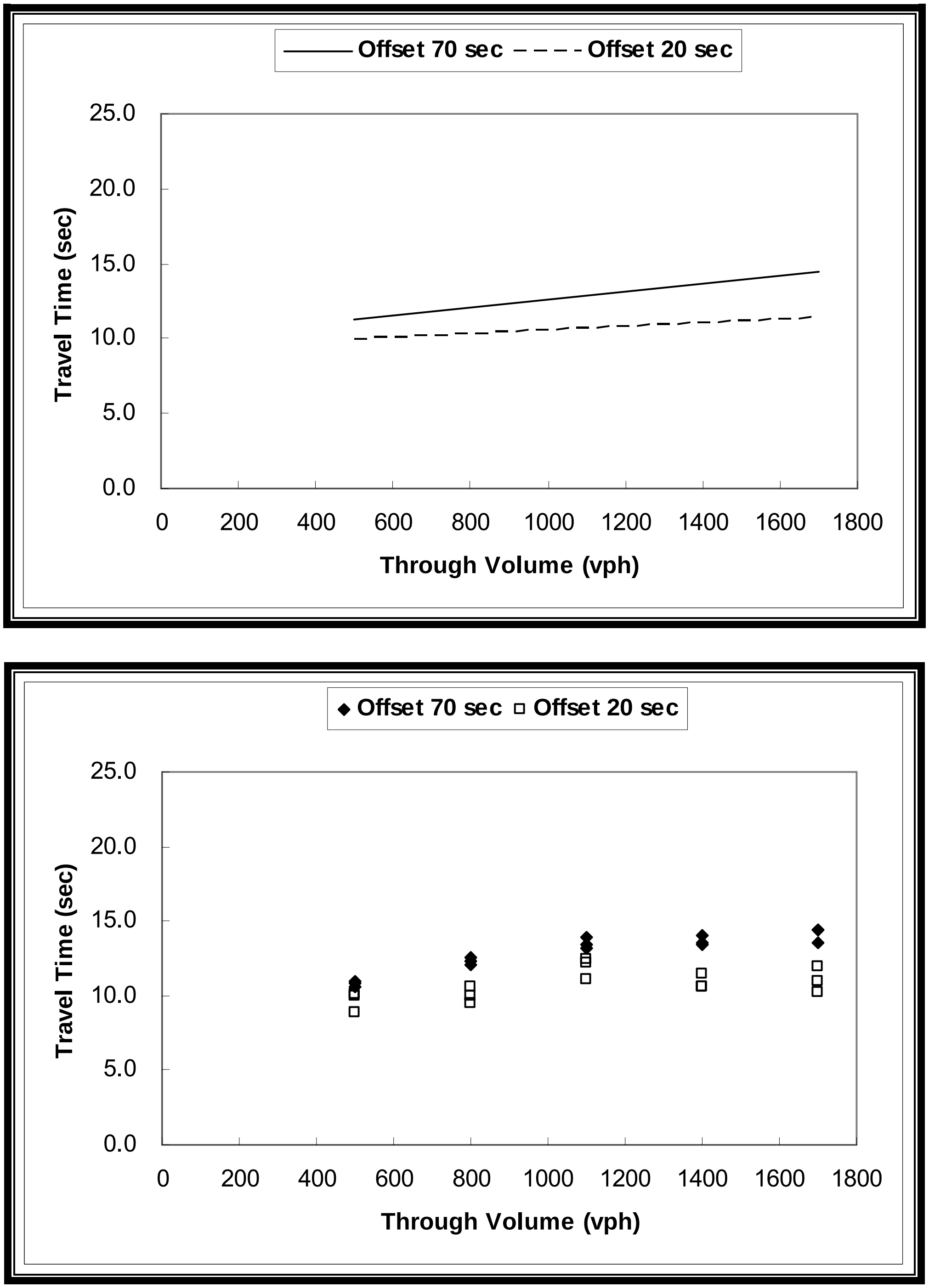


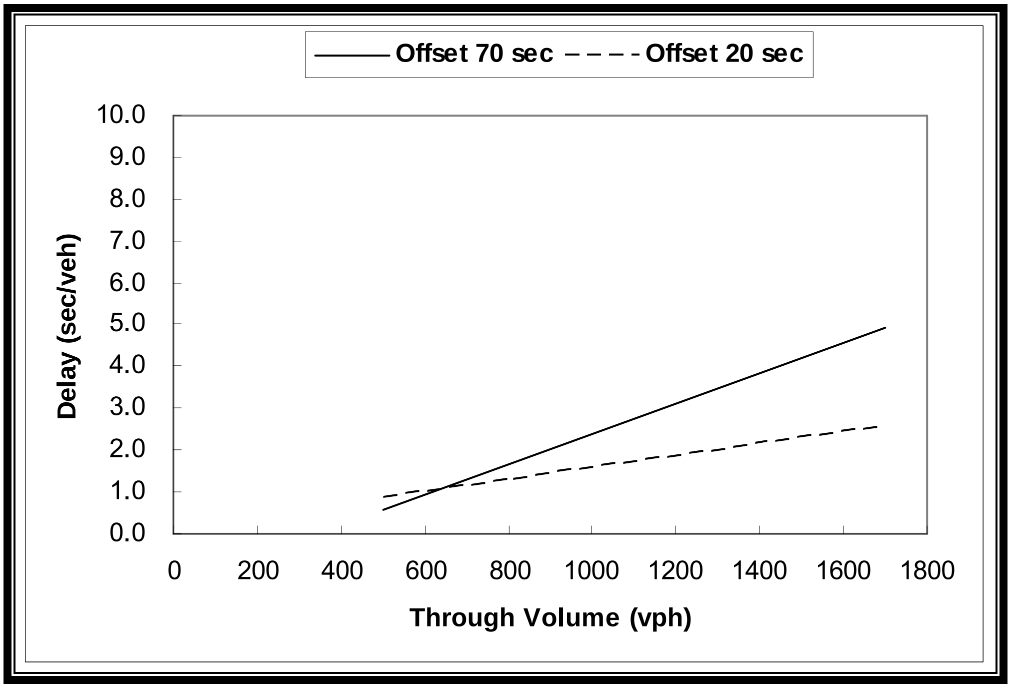
Figure 4.8 Effect of Offset on Travel Time of Non-Stopping Weaving Vehicles

greater than for Scenario 2. This result reveals that the travel time for offset of 70 sec is more likely to be affected by the arterial through volume than for offset of 20 sec.

The multiple data points resulted from the different percentage (25, 50, and 75 %) of weaving vehicles are plotted in the lower graph of Figure 4.8. There are data points at a particular volume level because of the multiple percentage of weaving vehicles turning right from the ramp terminal. The examination of this figure represents that the data points are more concentrated at a particular through volume level than the data points plotted in the bottom graph of Figure 4.7 at the same through volume. Thus, the travel time of non-stopping weaving vehicles is less likely to be affected by the percentage of weaving vehicles.

The next examination was conducted to check the effect of different offsets between the ramps on the delay caused by weaving vehicles stopping on the free right-turn lane. As Figure 4.9 indicates, the relationship between delay on the free right-turn lane and arterial road volume for Scenarios 2 and 3 is similar to the relationship between the travel time on the weaving section and the arterial through volume.

The upper graph in Figure 4.9 shows that as the arterial through volume increased, the delay also increased for Scenarios 2 and 3. The increase in delay on the free right-turn lane was found to be 2.5 seconds greater for Scenario 3 than Scenario 2. In other words, the delay for an offset of 70 sec is more likely to be affected by the arterial through volume than for an offset of 20 sec. However, the best fit lines meet each other at the through volume of 600 vph. This result reveals that there is little difference between delay for Scenarios 2 and 3 at the lower through volume level.



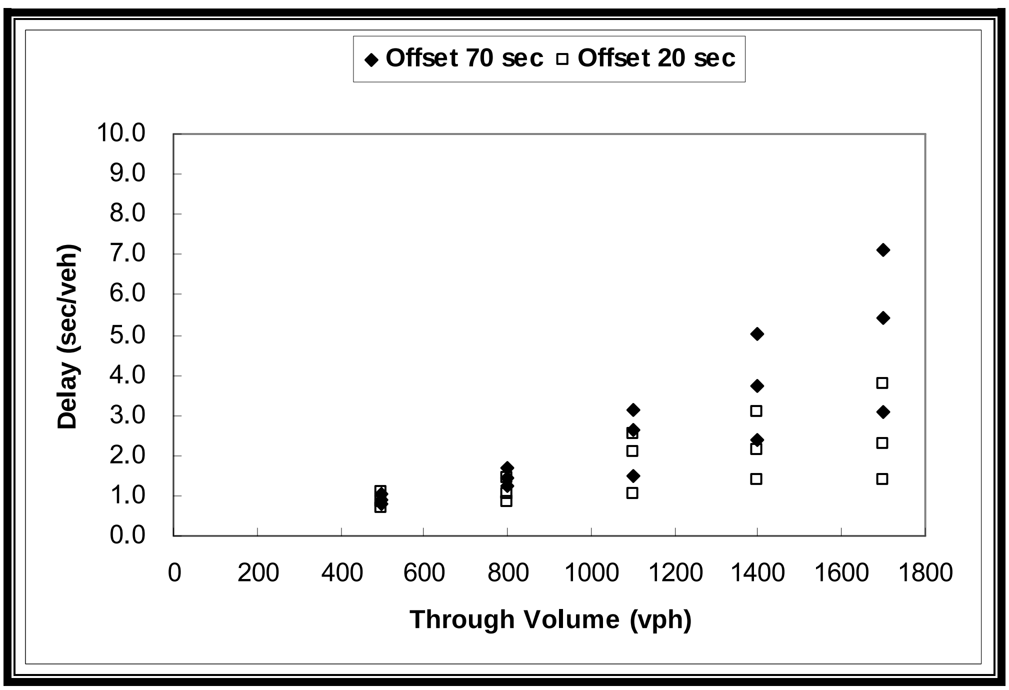


Figure 4.9 Effect of Offset on Free Right-Turn Lane Delay

The lower portion of Figure 4.9 plots the actual data points used to draw the best fit lines shown in the upper part of Figure 4.9. While the data points show scatter at the higher through volumes, the data points are more concentrated at the lower through volumes. Each point at a particular through volume level is due to the different percentage (25, 50, and 75 %) of weaving vehicles exiting from the ramp terminal, and the data point is highly located at a particular volume level when the percentage of weaving vehicles is higher. Thus, the delay on the free right-turn lane is more likely to be influenced by change of the percentage of weaving vehicles at higher arterial through volumes than lower arterial through volumes.

At the through volume of 500 vph, the data points for offsets of 70 and 20 sec overlap each other. It is indicated by the results of this figure that the difference in free right-turn lane delays between internal offsets of 70 and 20 sec is smaller at low through volumes than at high through volumes.

Statistical analysis using the paired *t*-test was conducted to determine if the offset values significantly affected delay. Table 4.5 provides the results of this *t*-test for mean delay. The result indicates the rejection of the hypothesis that the mean delays were equal at a 95% confidence level. Thus, the internal offset between the two signals of the ramp terminals has significant influence on the delay caused by stopping weaving vehicles on the free right-turn lane.

Since the offset of 20 sec is equal to two seconds less than travel time between upstream and downstream ramp terminals, the green signal for through movements (Overlap B: $\Phi5+\Phi6$) turns on when the through traffic vehicles passing by the upstream ramp arrive at the downstream ramp terminal. Because of this, vehicle platoons just passing by the upstream ramp do not stop at the downstream ramp, and they are dispersed when the platoon passes by the downstream ramp terminal. This platoon dispersion is likely to provide enough gaps for the weaving vehicles turning right on the free right-turn lane. In the case of the 70 sec internal offset, however, since this offset results in bad progression and longer queues on interior lanes, gaps for the weaving movement are less likely to be provided enough at the downstream ramp terminal during the green phase for arterial through traffic (Overlap B: Φ5+Φ6).

Table 4.5 Paired *t*-Test Between Scenarios 2 and 3 for Delay

	Scenario 2 (20 sec Offset)	Scenario 3 (70 sec Offset)
Mean	1.67	2.28
Num. of Sample	42	42
Variance	0.89	2.27
Degree of Freedom	41	
Calculated *t*-value	-4.19	
Critical *t*-value	2.02	
Significance value	0.0	

Effect of Auxiliary Lane

In this section, the influence of the exclusive receiving lane on the free right-turn lane delay was examined by comparing Scenarios 2 and 4. The geometric conditions of Scenario 2 included auxiliary lane for right turns on the departure leg, as was found in the field site. In the case of Scenario 4, the auxiliary lane was removed from the departure leg, and the free right-turn lane was YIELD-controlled.

The examination did not consider the relationship between total travel times of weaving maneuvers and the various through volumes since this section was concentrated on the effects of an exclusive receiving lane on the delay of the free right-turn lane. The weaving vehicle percentages of 10, 30, 50, 70, and 90 percent were coded into the computer simulation runs for these two scenarios.

The upper portion of Figure 4.10 shows the best fit lines for the relationship between the delay and the arterial through volume for Scenarios 2 and 4. The delay tends to increase as the arterial road volume increases, and the increase in delay is found to be 2 seconds greater for Scenario 4 than for Scenario 2. The slopes of the fit lines reveal that arterial through volume has a greater effect on the delay on the free right-turn lane for Scenario 4 than for Scenario 2. Moreover, in both cases, as the arterial through volume increases, the slopes of the lines in the upper graph of Figure 4.10 tend to be increased.

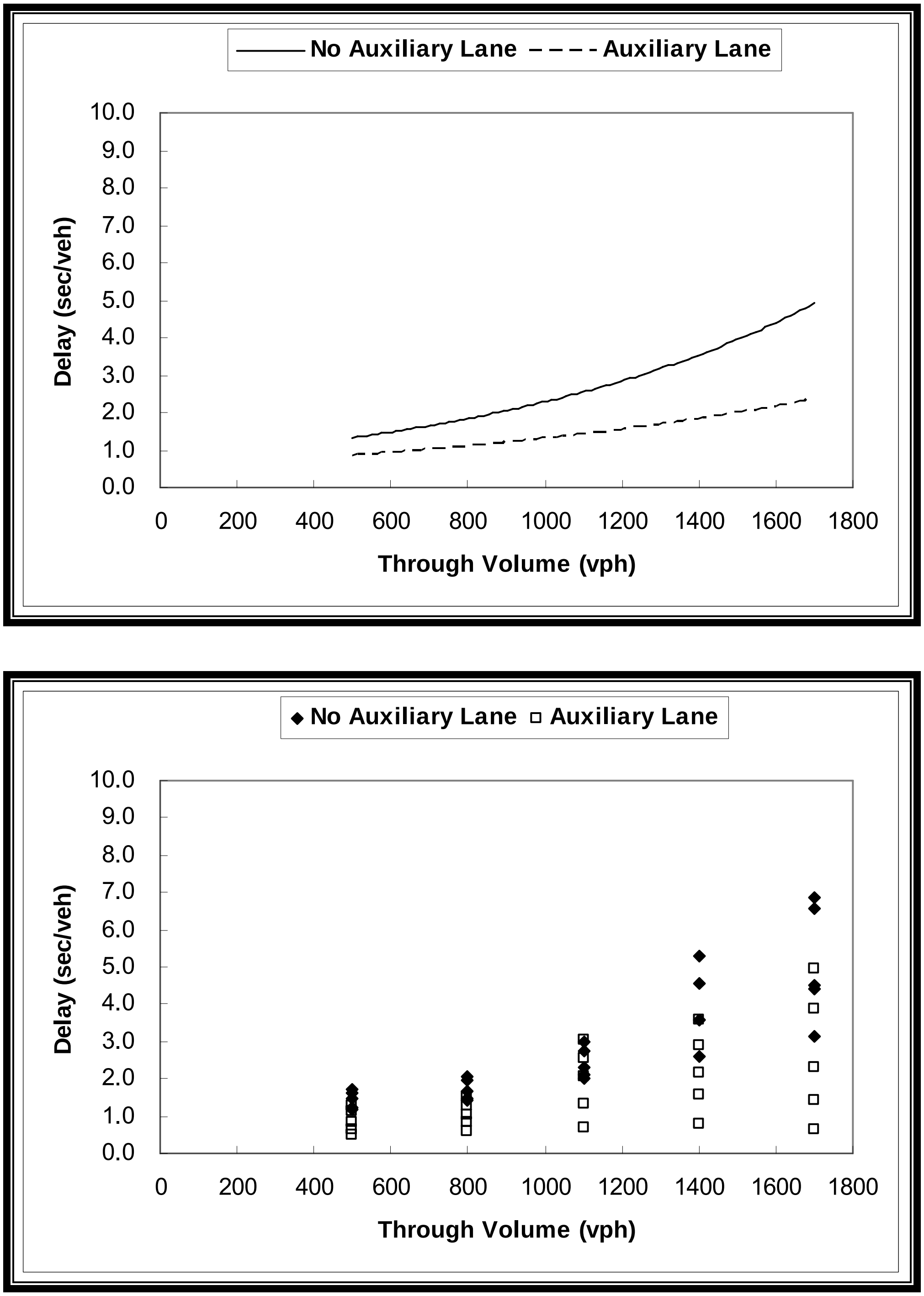


Figure 4.10 Effect of Auxiliary Lane on Free Right-Turn Lane Delay Versus Arterial Through Volume

It is also observed that there is little variation at the low through volume between the data points resulting from the multiple weaving vehicle percentages. As shown in the upper portion of Figure 4.10, the difference between fit lines of both cases is small at the low through volume.

The bottom portion of Figure 4.10 illustrates the variability in delay versus arterial road volume. As indicated by the data points in this graph, the variance increased when the arterial through volumes increased, especially for Scenario 2. Therefore, the free right-turn lane delay was more likely to be affected by the weaving vehicle percentages at the high through volume than at the low through volume. The higher positioned points resulting from the higher percentage of weaving vehicles at a particular through volume for Scenario 2 overlap in the range of the variance of the data points at the same through volume for Scenario 4.

Next, the relationship between delay and the percentage of weaving vehicles turning right on the free right-turn lane was examined. As indicated by the upper graph of Figure 4.11, the delay on the free right-turn lane increased when the percentage of weaving vehicles increased. However, the steeper slope for Scenario 2 indicated that the rate of change of the delay for this case was greater than for Scenario 4.

The actual data points resulting from the computer simulation runs for Scenarios 2 and 4 are shown in the lower graph of Figure 4.11. When the weaving percentage increased, the increase in the variance of the data points for Scenario 2 was greater than for Scenario 4. This result indicated that the percentage of weaving vehicles exiting from the free right-turn lane had a greater effect on delays for an exclusive receiving lane.

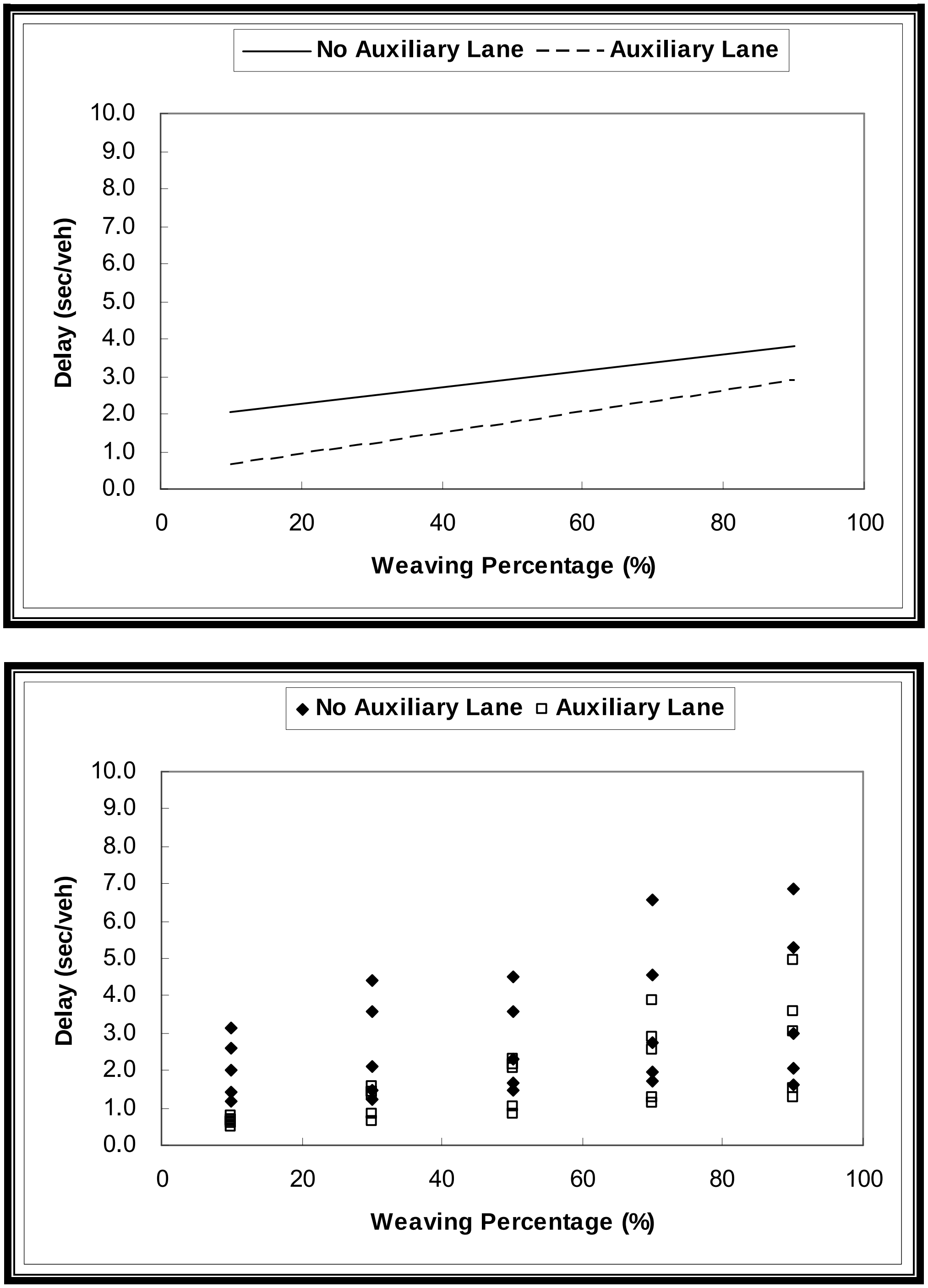


Figure 4.11 Effect of Auxiliary Lane on Free Right-Turn Lane Delay Versus Weaving Vehicle Percentage

Additionally, the rate of overlap between the data points for Scenarios 2 and 4 at a particular percentage of weaving vehicles tends to increase when the percentage of weaving vehicles increases. This result indicates that the volume, including weaving and through volume, warrant should be developed for an exclusive receiving lane for right-turn movement.

Free Right-Turn Lane Delay Relationships

In reviewing the effects of traffic signals, internal offset timing, and an exclusive receiving lane for right turns on the operations of the free right-turn lane, several operational problems caused by weaving vehicles stopping on the free right-turn lane became apparent. For analysis and model development of delay on the free right-turn lane, regression analysis was performed on variables that appeared to affect the operation of the weaving maneuvers and the free right-turn lane. This section provides the relationship between the variables and the delay caused by the weaving vehicles stopping on the free right-turn lane.

The effects of the following variables on the delay of the free right-turn lane were examined:

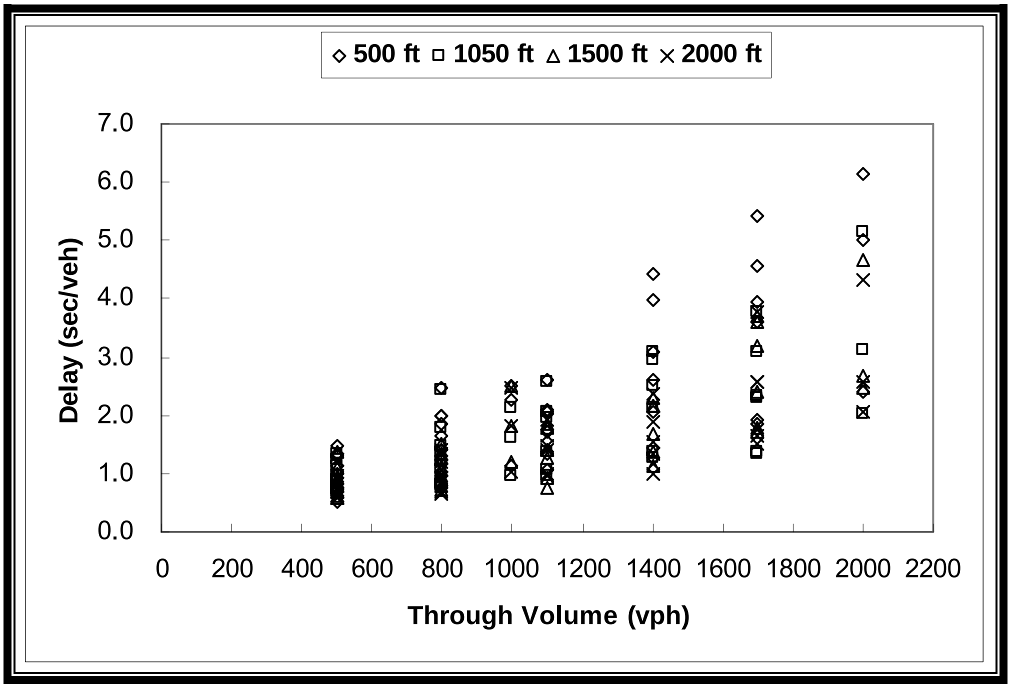
- Through volume on the arterial road;
- Distance between diamond interchange ramp terminals;
- Number of through lanes on the arterial road; and
- Weaving volume.

As shown by Figure 3.8 in the previous chapter, the delay on the free right-turn lane (link 12-13) was provided by CORSIM simulation model under the various conditions. Since the number of variables considered was large, it was very complicated to organize the outputs for the delays obtained from the computer simulation model. The simulation outputs were organized by the geometric configuration variables such as the distance between the two ramp terminals and the number of lanes of arterial road. These outputs were used for several plots made to show the effect of the various conditions on the free right-turn lane delay like the relationships that were examined previously.

Effect of Arterial Through Volumes

As indicated in Figure 4.12, the first relationship that was examined was the effect of the arterial through volume on the delay caused by the weaving vehicles stopping on the free right-turn lane. The best fit lines and the actual data points are plotted in the upper and lower graphs of Figure 4.12, respectively.

The slopes of the best fit lines in the upper graph of Figure 4.12 show that the delay on the free right-turn lane is increased when the arterial through volume increases. For 1050, 1500, and 2000 ft distances, the increase in the free right-turn lane delay is close to each other, and the difference between the delays is small at a particular through volume.



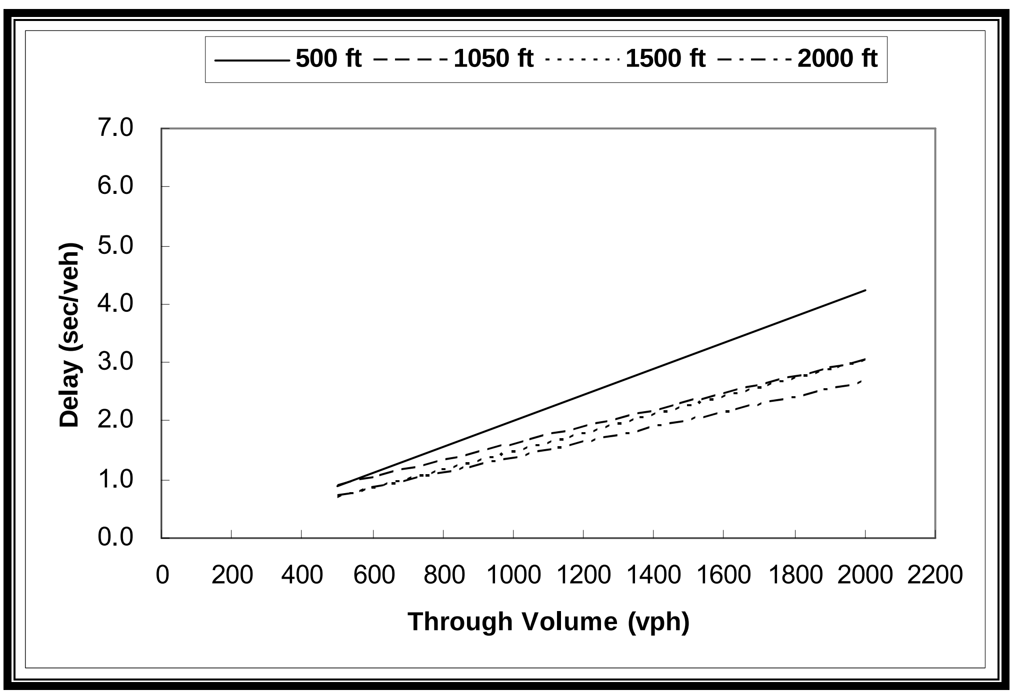


Figure 4.12 Effect of Arterial Through Volume on Free Right-Turn Lane Delay

It is indicated by the convergence of the best fit lines at the higher distances that there is little to be gained when the distance is increased beyond 1050 ft. These fit lines also reveal that the arterial through volume has a greater effect on the delay for the 500 ft distance than for the longer distances. At the lower through volume, the difference between the delays for each distance is very small.

The lower graph of Figure 4.12 illustrates the data points and the variability of the delay against various arterial through volume. In general, the variance increased as the through volumes increased. The data points for the shorter distance, especially 500 ft, indicate that the delay on the free right-turn lane tends to be scattered as the arterial road volume increases beyond 1400 vph. These results reveal that the distance between the two ramps has influence on the free right-turn lane delay because the longer distance between two ramp terminals allows more platoon dispersion to occur, giving weaving drivers longer headways.

Effect of Distance between Two Ramps

The second examination was conducted to see the relationship between the delay and the various distances between the two ramp terminals. The top portion of Figure 4.13 indicates the best fit lines of this relationship, and the bottom portion plots the data points obtained from the computer simulation runs.

As the best fit lines in the top portion of Figure 4.13 indicate, the delay on the free right-turn lane tends to decline as the distance between the two ramp terminals increases. The decrease in delay for one lane was found to be similar to the decrease for

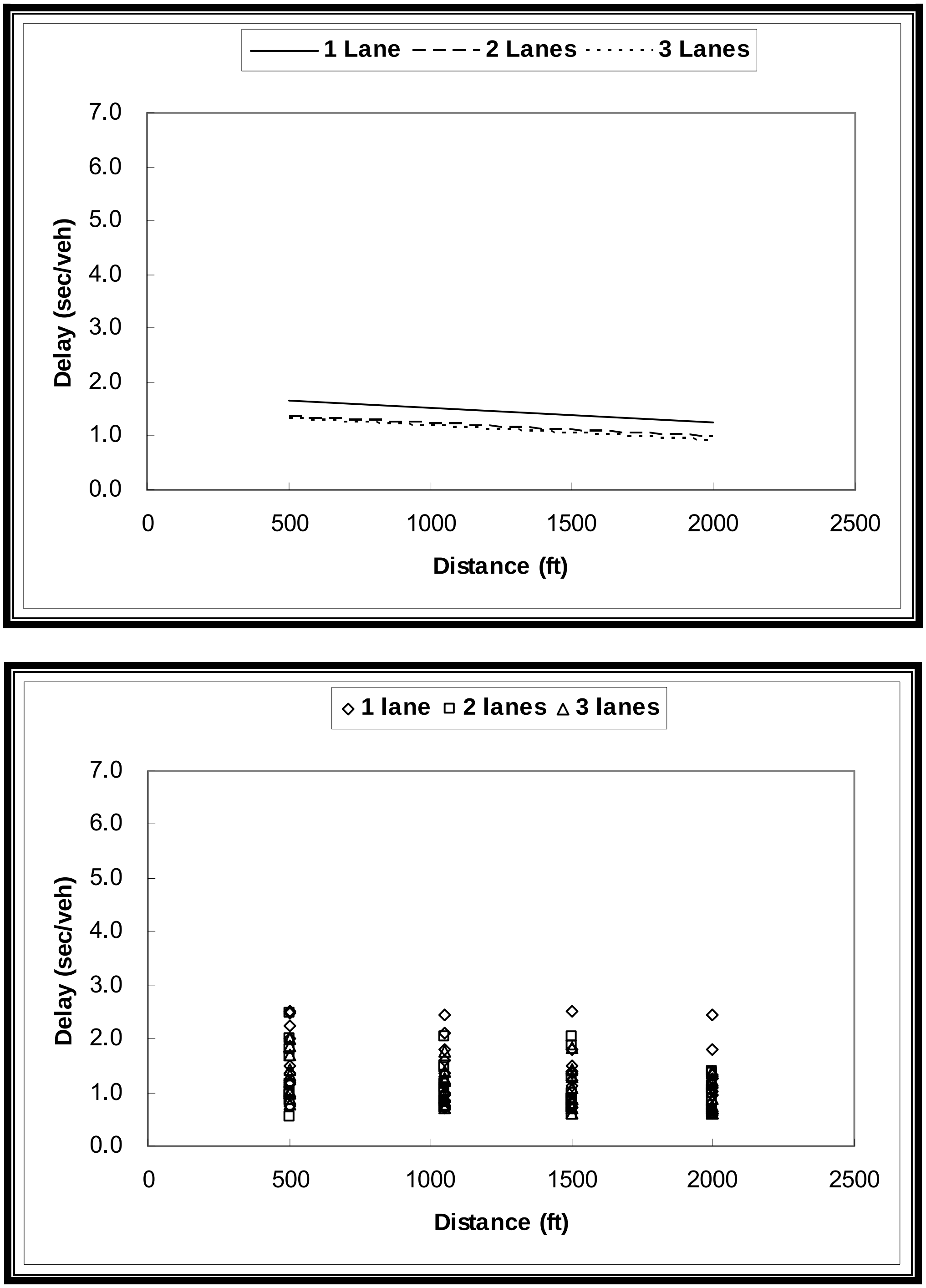


Figure 4.13 Effect of Ramp Spacing on Free Right-Turn Lane Delay

two or three lanes. In the cases of two and three lanes for the arterial through traffic, however, the differences between the delays at a particular distance were very small. For two or three lanes, the apparent convergence of the fit lines indicates that there is little to be gained by adding the third lane.

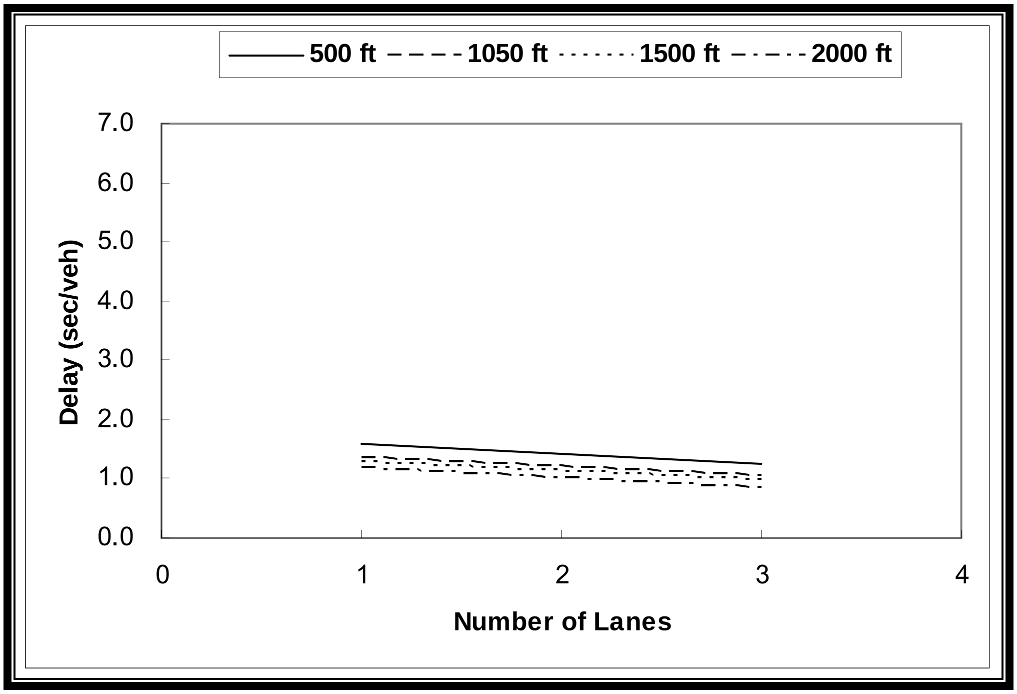
The variation in delays for each simulated number of lanes is shown in the bottom portion of Figure 4.13. According to this figure, the number of lanes also affected the operation of the free right-turn lane.

Effect of Number of Lanes on Arterial Road

As indicated by the fit lines in upper portion of Figure 4.14, the delays tended to decline as the number of lanes increased. However, the 95% confidence interval of each fit line's slope includes zero, so it can be concluded that these slopes are not significantly different from zero. Thus, the number of lanes might not be a proper variable to describe the free right-turn lane delay. The 95% confidence intervals are listed in Table 4.6.

Table 4.6 95% Confidence Interval of Slope

Ramp Spacing (ft)	Significance Value	95% Confidence Interval of Slope	
		Lower	Upper
500	0.18	-0.45	0.09
1050	0.18	-0.37	0.07
1500	0.17	-0.39	0.07
2000	0.06	-0.37	0.01



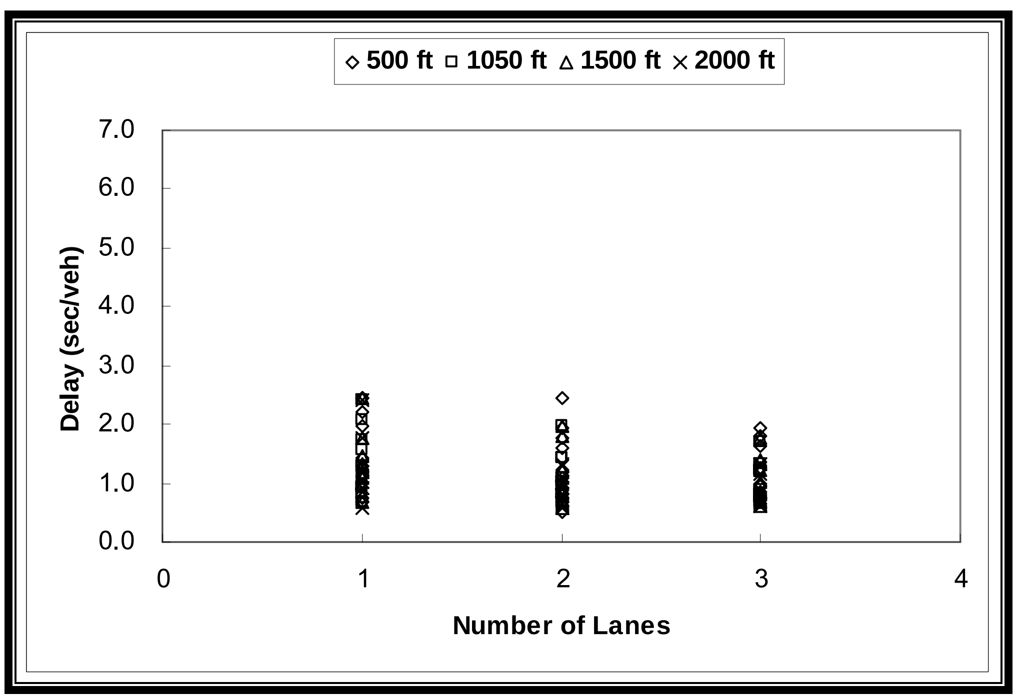


Figure 4.14 Effect of Number of Lanes on Free Right-Turn Lane Delay

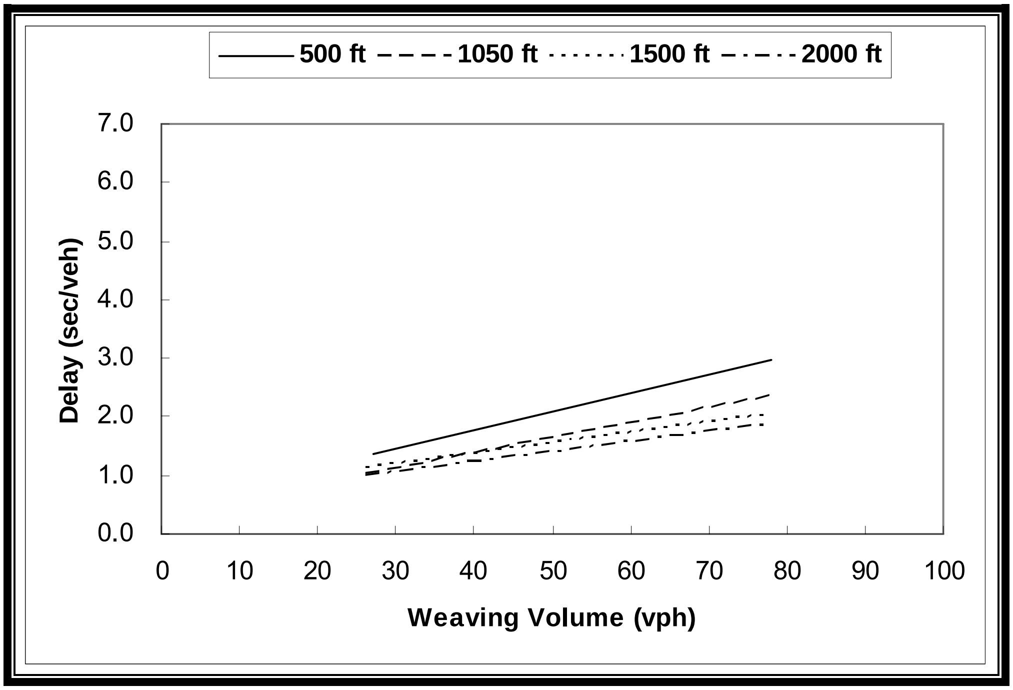
According to the lower portion of Figure 4.14, the variance decreases when the number of lanes is increased. The multiple data points at the particular number of lanes were obtained for the various weaving percentages. Thus, the spread between data points from the same distance at the particular number of lanes reveals that the weaving volume also has effect on the operation of the free right-turn lane such as the delay.

Effect of Weaving Volumes

Finally, the relationship between the delays on the free right-turn lane and the various weaving volumes was examined. The best fit lines and the data points obtained from the computer simulation runs are shown in the upper and lower graphs of Figure 4.15, respectively.

As the top portion of Figure 4.15 illustrates, the free right-turn lane delay tends to increase when the weaving volume increases. The best fit lines also represent that the weaving volume has a greater effect on the delay at the 500 ft distance than at the larger distances. For the 1050, 1500, and 2000 ft distances, the difference between the delays at the lower weaving volumes was very small.

The variance in the delay increased as the weaving volume increased, as shown in the bottom of Figure 4.15. The multiple data points were collected from the computer simulation runs under the various conditions, such as the arterial through volumes and the number of lanes of arterial road. Once again, as the weaving volume increased, the variance for the 500 ft at all weaving volume levels is more likely to be increased than for other distances.



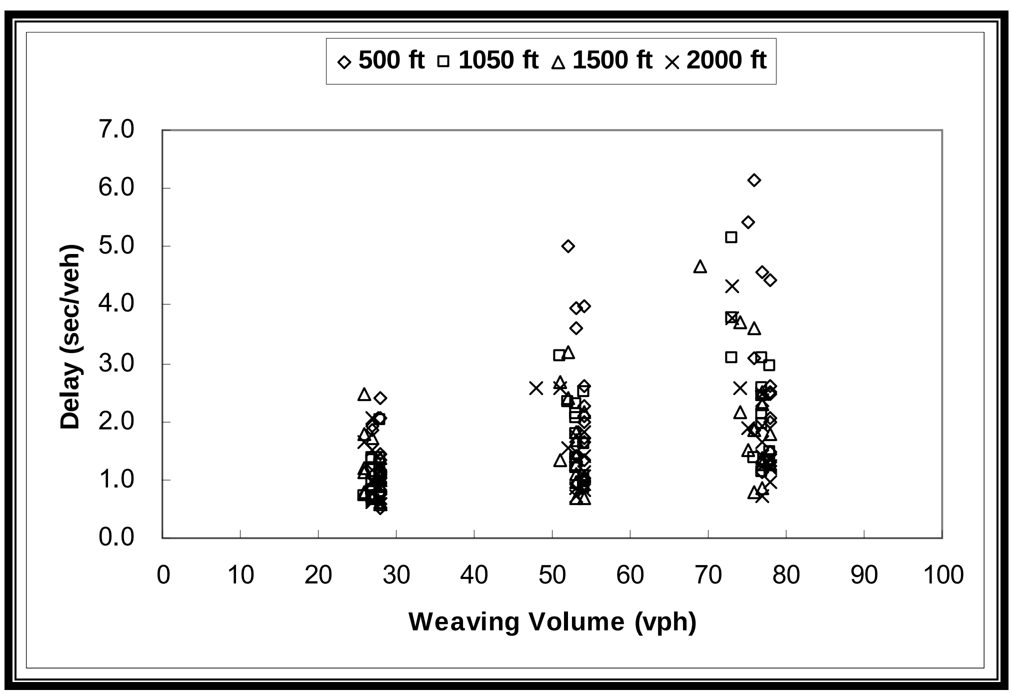


Figure 4.15 Effect of Weaving Volume on Free Right-Turn Lane Delay

MODEL DEVELOPMENT

After the free right-turn lane delay relationships were derived, an analytical model was developed to predict the operations and the delay of the free right-turn lane at the ramp terminal of a diamond interchange. This section consists of the following parts: model formulation and validation.

Model Formulation

Variables that should be included in the model for describing the free right-turn lane delay were identified through the results discussed in the previous sections and knowledge of traffic flow theory. As discussed earlier, the following factors were selected as the variables that were believed to affect the weaving operations causing delay on the free right-turn lane at the ramp terminals:

- Through volume on the arterial road;
- Distance between the interchange ramp terminals;
- Arterial road geometry (number of lanes); and
- Weaving volume.

Although each variable could not independently explain all of the variation in delay on the free right-turn lane, each variable had a noticeable effect on the free right-turn lane delay. It is believed that most of the variation in free right-turn lane delay will be explained when all of these variables are included in the model.

The SAS statistical analysis package was used to develop linear regression equations. Since all of the delay relationships presented in the previous section appear to be linearly related to free right-turn lane delay against the variables, the linear regression procedure was chosen for the model formulation.

The coefficient of determination, R^2, measures the proportion of the variability in the response variable, free right-turn lane delay, that is explained by the explanatory variables in the model (*28*). Therefore, a preliminary analysis was conducted to examine the effect that each explanatory variable had on the coefficient of determination of the model. Although each variable could not independently explain all of the variation in delay on the free right-turn lane, most of the variation in delay will be explained when all of the response variables are included in the model. However, some of these candidate variables might not be necessary to adequately develop the free right-turn lane delay model.

The result of the preliminary analysis indicated that separate equations for each geometric configuration (number of lanes on arterial road) resulted in better correlations than one equation for all geometric configurations. This result was also illustrated by the slope of the fit lines indicating the relationship between number of lanes and free right-turn lane delay discussed in previous section (Effect of Number of lanes on Arterial Road). For this reason, separate linear models were developed for each geometric configuration. Thus, a total of three models were developed: one-, two-, and three-lane. All of geometric configurations included an auxiliary lane for right-turn traffic on a departure leg within the weaving section.

The resulting equations for each configuration were of the following general form:

$$Delay = a + b\,(V_{TH}) + c\,(V_W) - d\,(L) \tag{4}$$

where:

Delay	= Free right-turn lane delay caused by stopping weaving vehicles (sec/veh);
V_{TH}	= Through volume on arterial road (vph);
V_W	= Weaving volume (vph);
L	= Distance between interchange ramp terminals (ft); and
a, b, c, d	= Regression coefficients.

The coefficient of determination, R^2, for each configuration was obtained from SAS, and these regression coefficients vary slightly. The resulting equations and the R^2 values are listed in Table 4.7. The *p*-value for each variable was also examined to explain the variation in the delay using the SAS outputs. Since all of these *p*-values were less than a significance level of 0.05, all of variables included in the three models helped to account for a statistically significant amount of variation in the delay. The statistical outputs obtained from the SAS are shown in Appendix B.

The variables with positive coefficients such as the arterial through and weaving volumes indicated that the expected delay increased when one of these volumes increased and no other variables changed. Similarly, as the distance between two ramps with the negative coefficients increased, the delay tended to decrease. These trends were consistent with the results indicated by the plots in the previous section, so it can be concluded that the regression equation was consistent with previous results.

Table 4.7 Regression Equations to Predict Free Right-Turn Lane Delay

GENERAL FORM:

$$Delay = a + b\,(V_{TH}) + c\,(V_W) - d\,(L)$$

Configuration of Arterial Road	Constants			
	a	b	c	d
One Lane (R^2=0.83)	-0.42355	0.00146	0.0194	0.00026
Two Lanes (R^2=0.79)	-5.9947	0.00162	0.0237	0.00061
Three Lanes (R^2=0.81)	-1.29694	0.00188	0.02551	0.00038

Model Validation

Once the model was developed, model validation was performed using field data in order to check the models' prediction ability. The analytical model developed in this study included various geometric configurations such as the number of lanes and the distance between two ramp terminals. Due to time and financial constraints, however, the field data for this study was available for only two lanes on the arterial road and the distance of 1050 ft. Thus, these field data under these geometric configurations were used to validate the formulated model.

Statistical measures were performed for quantifying the difference between the simulated and the observed data. A paired *t*-test was used to compare the measured free right-turn lane delays with the predicted free right-turn lane delays. First, the time periods that were not used for the model calibration were selected for the model validation. These time periods used for the model validation are shown in Table 4.8.

Table 4.8 Time Periods and Configuration Used for Model Validation

Time Period	Distance Between Two Ramp Terminals (ft)	Number of Lanes on Arterial Road
8:00 - 8:15 A.M 8:30 - 8:45 A.M 10:30 - 10:45 Noon 11:15 - 11:30 Noon 12:30 - 12:45 P.M 2:15 - 2:30 P.M	1050	2

Two 15-minute periods each were chosen for A.M., noon, and P.M. periods. The 15-minute through volume and weaving volume for each time period were converted to hourly flow rates. These validation data in addition to the distance and the number of lanes were input into the formulated model. The predicted delays were compared with the observed delays, and these values were also statistically compared using a paired *t*-test. The comparison and the results of the paired *t*-test are listed in Tables 4.9 and 4.10, respectively.

Table 4.9 Comparison Between Predicted and Observed Delay

Time Period	Arterial Road Volumes (vph)	Weaving Volumes (vph)	Predicted Delay (sec/veh)	Observed Delay (sec/veh)
8:00 - 8:15 A.M	998	68	2.0	2.2
8:30 - 8:45 A.M	756	52	1.2	0.9
10:30 - 10:45 Noon	668	40	0.8	1.2
11:15 - 11:30 Noon	657	64	1.3	1.6
12:30 - 12:45 P.M	664	60	1.3	1.5
2:15 - 2:30 P.M	728	64	1.5	1.7
Average			1.3	1.5

Table 4.10 Paired *t*-Test Between Predicted and Observed Delay

	Predicted Delay	Observed Delay
Mean	1.35	1.53
Num. of Sample	6	6
Variance	0.15	0.21
Degree of Freedom	5	
Calculated t-value	1.83	
Critical t-value	2.57	
Significance value	0.126	

As indicated by the data listed in Table 4.10, there were no significant differences between the observed and the predicted delay at a 5% level of significance. Therefore, the model developed in this study is not contradicted by the field data, and is a reasonable candidate model for predicting the free right-turn lane delay caused by stopping weaving vehicles.

After developing the analytical model, the applicable range of the model must be specified. This range was dependent on the range of variables input into the computer simulation model. In this study, the variables that limited the range are the number of lanes, arterial road volume, and weaving volume. Before using the model for one and three-lane on arterial road, model validation should be conducted for these two cases with field data. The applicable volume ranges for the model for each number of lanes are listed in Table 4.11.

Table 4.11 Applicable Volume Ranges for Model Limitations

Configuration of Arterial Road	Arterial Road Volume (vph)		Weaving Volume (vph)	
	Minimum	Maximum	Minimum	Maximum
One Lane	500	1000	20	200
Two Lanes	500	2000	20	200
Three Lanes	500	3000	20	200

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This chapter provides the conclusions drawn from results obtained in the research. The recommendations for implementation and future research are also presented at the end of the section. While the models developed in this research are useful for studying weaving maneuvers on certain arterial road configurations, other situations that are encountered on arterial roads are not addressed by these models and should be addressed in future studies.

The objectives of this thesis were divided into two main parts. The first objective was to identify variables that affect an arterial weaving section between a ramp terminal and a downstream intersection. The second was to determine the effect of arterial weaving maneuvers on the operations of the free right-turn lanes under various geometric and traffic characteristics on the arterial weaving section. The characteristics examined for this study were:

- Distances between interchange ramp terminals of 500, 1050, 1500 and 2000 ft;
- Number of lanes of one, two and three lanes on the arterial road;
- Arterial through volumes of 500, 800, 1100, 1400, 1700 and 2000 vph;
- Weaving percentages of 25, 50, and 75%; and
- Offsets between the traffic signals of ramp terminals of 20 and 70 sec.

The CORSIM microscopic traffic simulation model was used to determine the variables affecting the operations of the weaving maneuvers on the arterial road and the free right-turn lane. The conclusions and recommendations based on the results of CORSIM simulation model addressed these objectives.

CONCLUSIONS

Field data were collected for basic observations and to calibrate CORSIM simulation that allowed traffic engineers to study the operations of the arterial weaving section under various traffic conditions. A linear regression model was developed to describe the delay caused by the stopping weaving vehicles on the free right-turn lane. From the analysis provided in this research, the following was concluded:

1. A relatively short distance between an exit ramp terminal and a downstream intersection on the arterial road can adversely impact operations of a free right-turn lane. Weaving drivers turning right at the ramp terminal and turning left at the downstream intersection may be forced to slow or stop on the free right-turn lane when they do not have sufficient gaps between through vehicles on the arterial road. Sufficient gaps would allow the weaving drivers to weave safely across the arterial road lanes, and these gaps are usually expected to be influenced ed by various traffic and geometric conditions, such as traffic signals on the arterial road, offsets between the ramp terminals, arterial through volumes, number of lanes, and distance between the ramp terminals.

2. Based on the analysis of field data collected at the study site, arterial through volumes were found to affect travel times of all and non-stopping weaving vehicles on the arterial road and delay caused by stopping weaving vehicles on the free right-turn lanes. Travel times of all weaving vehicles increased as the arterial through volume increased, and travel times of non-stopping weaving vehicles were relatively constant as the arterial through volume increased. Free right-turn lane delay increased when the arterial through volume increased.

3. The results of the calibration procedure for the computer simulation model reveal that the percentage of vehicles that would slow down to allow for a lane changer has a much greater effect on simulation performance that the other parameters that can be adjusted. Based on the results of the comparison of the computer simulation data and the field data, the calibration was performed to achieve good agreement between the simulated MOE and observed MOE.

4. Introduction of signals was found to have significant influence on the outputs produced by CORSIM. The introduction of signals affects the headway distribution of through traffic, and makes dense platoon on the arterial road. This dense platoon makes weaving vehicles difficult to weave. Thus, traffic signals impact the vehicles attempting to merge into through movements.

5. Progression was found to affect the operations within the arterial weaving section that was studied. The two offsets between the ramp signals were used to see the progression effect, and the results produced by CORSIM indicate that

progression has significant influence on the delay caused by the stopping weaving vehicles on the free right-turn lane. The better the quality of progression, the easier the weaving maneuvers to merge into through movements.

6. Based on the computer simulation results, relationships between free right-turn lane delay and traffic and geometric conditions were established in this study. After investigating simulated performance under various factors, linear regression models were developed for each of three configurations to predict the delay caused by the stopping weaving vehicles on the free right-turn lane under various conditions.

RECOMMENDATIONS

Based on the results of this study, the following recommendations for implementation and further research are provided:

1. Before using the models developed in this research for one and three-lane arterial roads, the models need to be validated with field data for these two cases. Moreover, since the linear model produced in this research was validated for only one ramp spacing of 1050 ft within a diamond interchange, effort should be also made to validate the model for other ramp spacings with field data. The procedures used for model validation in this study could be applied to one and three-lane cases and other ramp spacing cases.

2. Further study of the effects of the number of acceptable gaps on operations of arterial weaving maneuvers and free right-turn lanes is needed. Based upon observations at the study site and the simulation outputs graphically shown by the TRAFVU program, offset and distance between the two ramp terminals influence platoon dispersion. Platoon dispersion allows right turning drivers to merge into the arterial road at the ramp terminal without stopping and waiting on the free right-turn lane.

3. A study should be conducted to observe the effects of link length between a ramp terminal and a downstream intersection on the operations of the arterial weaving section and the delay caused by the stopping weaving vehicles on the free right-turn lane. A longer length between the ramp terminal and the

downstream intersection lengthens the effective weaving area. The longer the link length, the easier the weaving maneuvers.

4. Further study of development of volume warrants for an auxiliary lane for right-turn vehicles on the departure leg is needed. The volume warrant study might be related to weaving volumes and arterial through volumes. Delay cost, and construction cost savings should also be considered for the volume warrant study.

5. An accident study should be conducted to determine the effects of the presence of the auxiliary lane for right-turn movements on the frequency, severity, and types of accidents at the ramp terminals. Since stopping vehicles usually are not expected on the free right-turn lane with the auxiliary lane on the departure leg, the stopping weaving vehicles on the free right-turn lane may cause safety problems.

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APPENDIX A

DATA REDUCTION SHEETS AND DIRECTIONS

Volume Log

Weaving Analysis Data Reduction Sheet

Site: Tape Number: Date: Analyst: Checker:

I/C	Start of G			Lane Volumes (veh)				Driveway Volumes (veh)		I/S	Start of G			LT Volume	Weaver Volumes		Initial Queue Length (veh)			
Cycle	hh	mm	ss	TH 1	TH 2	FRT	Illegal RT	In	Out	Cycle	hh	mm	ss	(veh)	Cars	Trucks	LT	TH 1	TH 2	TH 3
1										1										
2										2										
3										3										
4										4										
5										5										
6										6										
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29										29										
30										30										

Weaving Log

Weaving Analysis Data Reduction Sheet

Site: Date: Analyst: Checker:

	Start of Weave			End of Weave			Queue Length (veh)				I/C Signal Phase	Number of Stops					Vehicle Type	Success
Tape	hh	mm	ss	hh	mm	ss	LT	TH 1	TH 2	TH 3	(R/Y/G)	LT	TH 1	TH 2	TH 3	FRT	(C/T)	(Y/N)

Directions for Reducing Weaving Analysis Data

This document provides a description of the procedures for reducing the videotaped weaving analysis data. Two sheets will be used for the data reduction—a volume log for the traffic volumes and queue lengths for each tape, and a weaving log for specific characteristics of each weaving maneuver.

Before Beginning Collection

One volume log sheet will be used for each tape. Record the site, tape number, date of analysis, and the initials of the analyst at the top of the sheet. Note that at this point, the only site being studied is TX 6 (East Bypass or Earl Rudder Freeway) & FM 60 (University Drive), specifically the weaving maneuver for vehicles using the southbound free right turn lane from the frontage road and immediately turning left onto Glenhaven Drive. If one sheet is not enough to contain all of the data from a tape, continue the data reduction on a new sheet.

Because the weaving maneuvers are not expected to occur frequently, one weaving log will be used for all of the tapes. Record the site, date of analysis, and the initials of the analyst at the top of the sheet.

Data Collection Procedure

Volume Log

The volume log is divided into two sections. The left section is for the interchange (I/C) data (in this case, the interchange terminal for FM 60 and the southbound frontage road of TX 6), and the right section is for the intersection (I/S) data (in this case, the intersection of FM 60 and Glenhaven Drive). The following are descriptions of each column on the sheet:

Column A—I/C Cycle: This column is already filled with the numbers for each signal cycle at the interchange terminal.

Columns B, C, and D—Start of G: Record the time of the start of the through green phase for each interchange signal cycle, in hours (hh), minutes (mm), and seconds (ss). Use the time stamp in the upper right corner of the screen, from the tape counter. Start of green is defined as the point at which the green signal lenses are fully lit. It is not necessary to record the frame numbers for the start of green. The beginning of the cycle is defined as the start of green for the cycle.

Columns E, F, G, and H—Lane Volumes (veh): Record the number of vehicles crossing the stop line in the number one and number two through lanes of the interchange terminal in the columns labeled TH 1 and TH 2, respectively. Record the number of vehicles making the free right turn movement in the column labeled FRT, and record the number of vehicles making an illegal right turn maneuver from the southbound frontage road's signalized through lanes in the column labeled Illegal RT. Because vehicles will be continuously making the free right turn maneuver without being affected by the interchange terminal signal, continue to count these vehicles even after the start of red for the signal. The free right turn maneuver is considered complete when the vehicle's front tires cross the painted crosswalk line on the free right turn lane.

Columns I and J—Driveway Volumes (veh): Record the number of vehicles entering and exiting the driveway downstream of the interchange terminal in the columns labeled In and Out, respectively. The driveway volumes are counted with the interchange cycles. For the purposes of this count, the line separating the traveled way pavement from the gutter pavement can be thought of as the stop line. A vehicle enters the driveway when one of its front tires crosses from the traveled way pavement to the gutter pavement, and a vehicle exits the driveway when one of its front tires crosses from the gutter pavement to the traveled way pavement.

Column K—I/S Cycle: This column is already filled with the numbers for each signal cycle at the intersection (in this case, FM 60 and Glenhaven Drive).

Columns L-N—Start of G: Record the time of the start of the through green phase for each intersection signal cycle, in hours (hh), minutes (mm), and seconds (ss). Use the time stamp in the upper right corner of the screen, from the tape counter. Start of green is defined as the point at which the green signal lenses are fully lit. It is not necessary to record the frame numbers for the start of green. The beginning of the cycle is defined as the start of green for the cycle.

Column O—LT Volume: Record the volume of vehicles making the left turn movement at the downstream intersection. These volumes are counted with the intersection cycle.

Columns P, Q, R, and S—Initial Queue Length (veh): Record the length of the initial queue at each lane of the intersection approach. There is one exclusive left turn lane (LT), and there are three through lanes (TH 1, TH 2, and TH 3). The third through lane (TH 3) is a shared through/right turn lane.

Columns T and U—Weaver Volumes: Record the numbers of cars and trucks successfully making the weaving maneuver in their respective columns. The weaver volumes are counted on the intersection cycle when the weaver makes a left turn at the downstream intersection. Only vehicles starting from the free right turn lane or making the illegal right turn maneuver at the interchange terminal are considered to be weavers. Vehicles turning right from the driveway to the left turn lane are not weaving, but rather making permitted right turns.

Weaving Log

The weaving log sheet is to be used for multiple tapes, as space allows. Data is to be recorded for vehicles successfully completing the weaving maneuver (starting in the free right turn lane and ending in the left turn lane, and stopping if there is a queue in the left turn lane) and for vehicles failing to complete the maneuver (did not make it to the left turn lane, but indicated the intent to do so). The following are descriptions of each column on the sheet:

Column A—Tape: Record the tape number for the weaving maneuver.

Columns B, C, and D—Start of Weave: Record the time at which the weaving maneuver started, in hours (hh), minutes (mm), and seconds (ss). The weaving maneuver starts when the vehicle's front tires cross the painted crosswalk line on the free right turn lane.

Columns E, F, and G—End of Weave: Record the time at which the weaving maneuver ended, in hours (hh), minutes (mm), and seconds (ss). *If there is no queue in the left turn lane when the weaving vehicle enters it, or if there are moving vehicles that do not force the weaving vehicle to stop, the weaving maneuver is considered complete when all of the vehicle's tires have crossed the solid white line. If there is a queue, the weaving maneuver is considered complete when the vehicle stops behind the queue.* A failed weave ends when the vehicle's front tires cross the intersection stop line.

Columns H, I, J, and K—Queue Length (veh): Record the lengths of the queues in each intersection approach lane (number 1 through, number 2 through, and number 3 through) when the weaving vehicle is inside that lane. *Record the number of queued vehicles in front of the weaving vehicle in the left turn lane only if the weaving vehicle is forced to stop.* A vehicle, initially stopped in queue at the downstream signal, is considered queued until its rear tires cross the stop line.

Column L—I/C Signal Phase: Record the indication on the interchange through movement terminal signal (red, yellow, or green) at the start of the weaving maneuver.

Columns M, N, O, P, and Q—Number of Stops: Record the number of times, if any, that the weaving vehicle stops in each of the lanes (left turn, number 1 through, number 2 through, number 3 through, and free right turn) during the maneuver.

Column R—Vehicle Type: Record the classification of the weaving vehicle ("C" for car or "T" for truck).

Column S—Success: Record whether the weaving vehicle successfully completed the weaving maneuver ("Y" for yes or "N" for no).

APPENDIX B

SAS RESULTS

The REG Procedure
Model: MODEL1
Dependent Variable: D Delay

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	9.58082	3.19361	52.65	<.0001
Error	32	1.94089	0.06065		
Corrected Total	35	11.52171			

Root MSE	0.24628	R-Square	0.8315
Dependent Mean	1.39869	Adj R-Sq	0.8158
Coeff Var	17.60773		

Parameter Estimates

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	-0.42355	0.21352	-1.98	0.0559
VTH	Arterial Through Volume	1	0.00146	0.00019976	7.32	<.0001
VW	Weaving Volume	1	0.01940	0.00202	9.63	<.0001
DS	Distance between two ramps	1	-0.00025628	0.00007412	-3.46	0.0016

Parameter Estimates

Variable	Label	DF	Variance Inflation
Intercept	Intercept	1	0
VTH	Arterial Through Volume	1	1.00004
VW	Weaving Volume	1	1.00011
DS	Distance between two ramps	1	1.00007

The REG Procedure
Model: MODEL2
Dependent Variable: D Delay

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	52.59826	17.53275	83.49	<.0001
Error	68	14.27920	0.20999		
Corrected Total	71	66.87746			

Root MSE	0.45824	R-Square	0.7865
Dependent Mean	1.63582	Adj R-Sq	0.7771
Coeff Var	28.01316		

Parameter Estimates

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	-0.59947	0.24768	-2.42	0.0182
VTH	Arterial Through Volume	1	0.00162	0.00013883	11.69	<.0001
VW	Weaving Volume	1	0.02370	0.00267	8.87	<.0001
DS	Distance between two ramps	1	-0.00060629	0.00009751	-6.22	<.0001

Parameter Estimates

Variable	Label	DF	Variance Inflation
Intercept	Intercept	1	0
VTH	Arterial Through Volume	1	1.00040
VW	Weaving Volume	1	1.00042
DS	Distance between two ramps	1	1.00003

The REG Procedure
Model: MODEL3
Dependent Variable: D Delay

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	91.57640	30.52547	117.10	<.0001
Error	80	20.85516	0.26069		
Corrected Total	83	112.43157			

Root MSE	0.51058	R-Square	0.8145
Dependent Mean	1.83290	Adj R-Sq	0.8076
Coeff Var	27.85626		

Parameter Estimates

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	-1.29694	0.25028	-5.18	<.0001
VTH	Arterial Through Volume	1	0.00188	0.00011560	16.26	<.0001
VW	Weaving Volume	1	0.02551	0.00280	9.10	<.0001
DS	Distance between two ramps	1	-0.00037944	0.00010061	-3.77	0.0003

Parameter Estimates

Variable	Label	DF	Variance Inflation
Intercept	Intercept	1	0
VTH	Arterial Through Volume	1	1.00173
VW	Weaving Volume	1	1.00214
DS	Distance between two ramps	1	1.00042

VITA

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